AIR CAR DESIGN MANUAL

by Scott Robertson

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This book is dedicated to the hands-on engineers of the early twentieth century.

Introduction

"Isnt compressed air just air that's been squished together?"

---Joshua Green, age 10

It's that simple, right? You just push the air into a smaller space, and you have instant compressed air.

Yes and no.

If building an air car were a simple matter of installing an air motor and an air tank on a car, and driving down the street, we would have been driving air cars all along. I tried it once. I built a go-kart using a riding lawn mower chassis, a pneumatic drill, and a scuba tank. It ran great! It started so fast, even up a steep hill, that the rickety steering couldn't keep up, and it tried to go every which way. Trouble is, by the time I could get the steering straightened out, it was almost out of air. So you have to do things a certain way; although we're surrounded by enormous quantities of air that's been heated up to atmospheric pressure by the sun, to get that internal energy of air, a form of solar energy, into a usable form, takes more than luck and good intentions. We need real knowledge if we are going to proceed in some direction other than a random one. In these days of inflated prices and short budgets, inventors need to do their planning on paper, and save the parts expenditures for the day when they have solid plans to back them up. Trial and error is one way to learn a technical skill: it's the hard, slow, expensive way.

And yet, if dealing with this challenge were all that hard, there wouldn't be so many people out there, some of them still with us, who have built air cars. And there wouldn't have been air powered locomotives all over the place from 1890 to 1930, but there was. Unfortunately, most of the inventors who have tackled this challenge don't want to help other inventors compete with them. The rest, with few exceptions, have taken their secrets to their graves with them, or are acting like that's what they plan to do. Without exception, the inventors of self-fueling air cars have neglected to include in their patents any reason for us to believe that they had ever heard of the second law of thermodynamics. But if their inventions were some sort of perpetual motion machines, the U.S. Patent Office would have refused to grant them their patents. So the difficult part of this challenge remains: we must learn what compressed air really is, what really makes it tick, and how to use it most effectively in order to get all this free, solar-heat-laden atmosphere into air tanks cheaply.

The paradox is that, despite the seeming simplicity of the processes involved in compressing and expanding air, there are enough factors affecting each other in pneumatics that knowing the why and how of calculating these simple processes is not a simple matter. It's not that the math is hard. The problem, for the average inventor, is that books that have been written about compressed air were written for engineers. Bogged down in calculations that are only half explained, non-engineers mistake pneumatics for a technically difficult field and switch on the TV, forgetting about their deep desire to show Detroit how it should have been done, and going back to something harmless like inventing the better mousetrap.

In tribute to those who would rather not give up on their greatest dreams, I contribute this effort to put a simple process into simple words. To those who've always wondered, "Why not run cars on compressed air?" I say, *Keep asking questions, until all your questions are answered, then go ahead and build it!*

More power to us all!

---Scott Robertson, founder
Pneumatic Options
July 21, 1995

Chapter 1: Compressed Air is Solar Energy

Thermodynamics Is About Heat: The Air Engine Is A Heat Engine!

> "We take no stock in flimsy denials based on no better foundation than mental doubt. The operations of computation from the adopted facts and formulas work well within the scope of practical engineering, and it is safe to follow them until something better is found that is based upon an equally good foundation."
>
> Gardner D. Hiscox, Mechanical Engineer
> Compressed Air, 5th Edition, 1909

Once upon a time, scientists thought heat was some kind of substance contained within matter. But they were unable to weigh the substance, "heat." Many ingenious theories failed to explain this conflict between scientific belief and common knowledge. It eventually became clear that heat is really a form of energy which has no weight, but can enter into all substances. Thus, heat is measured by its effect on its host, matter: the energy known as heat does its work by expanding matter. Expansion means the molecules making up the matter vibrate faster, bounce against each other harder and more often, and therefore move farther apart from each other.

Temperature And Pressure Indicate Heat Energy

In the case of air, we detect the addition or subtraction of heat by measuring the air's temperature and pressure. Temperature measures how fast matter is vibrating. When we heat air, and its molecules move faster, we feel this as a warming of the air: the air molecules rub on your skin more, producing friction which warms you. To show that expansion accompanies a rise in air's temperature, consider the reaction of a piston in a combustion-engine cylinder when met with a sudden blast of heat. The expansion of air in the cylinder causes an undeniable event: the piston moves!

Pressure is a special condition of air that comes about when the air wants to expand because of the addition of heat, but can't. An air tank that you filled to 60 psi yesterday sat for awhile, and is now at room temperature. What happens if you take the tank outside and set it in the sun? The molecules in the tank will bounce around faster, the air will get warmer, and it will want to expand, but can't because it's trapped in the tank. If you look at the gauge on the tank, you'll discover that the pressure in the tank has gone up. The main point here is that if you heat air but don't let it expand, its pressure goes up. This means that **pressure is the desire of air to expand when it can't**. More simply, **pressure is the ability of air to expand.**

Compressed air is air that has the ability to expand, and the pressure (ability to expand) of a volume of air is measured by comparing it to atmosphere. Atmospheric pressure is considered zero gauge pressure since it generally has no desire to expand. So when we say air is at 60 psi pressure, we mean that it has 60 psi more pressure than atmosphere. Regular air around us has a little pressure too but it doesn't register on a gauge because it's trapped in such a huge tank--the earth's atmosphere--that its ability to expand is usually irrelevant, so we believe the gauge when it says atmospheric pressure is zero, and measure pressure in relation to atmospheric pressure as a baseline.

The need for this discussion of the nature of pressure is not obvious, but because of pressure's subtle nature we need all that much more to discuss it. We take compressed air for granted; it's simple to use, so we think it's too obvious to need explaining. But because of a general misconception about pressure in air, we have missed its greatest benefit, and have routinely denied the existence of this benefit, just because we think we know what pressure is before having ever thought about it. This misconception about pressure is as widespread as its neglected benefit would be sweeping in potential, if it were to be realized. The misconception is that Pressure Pushes Pistons; the benefit of compressed air that is neatly hidden by *Pressure Pushes Pistons* is that **compressed air can transmit more solar energy than we humans know how to use**! The sun can make us all energy-rich beyond our greediest dreams, and the tool for making this happen is ordinary compressed air combined with the appropriate hardware.

I mentioned above that when air is heated, the resulting expansion causes a rise in temperature and, if the air is trapped, a rise in pressure. To wipe *Pressure Pushes Pistons* out of your mind, you must learn to distinguish between *heat energy*, which is what really pushes pistons, and *temperature and pressure*, which only <u>measure</u> heat energy, or the <u>ability</u> to push pistons. Pressure is sometimes referred to as potential energy because it's a form of tension; static, stored energy waiting to do something, like a wound spring. Potential energy doesn't do anything; it <u>wants</u> to do something. It's useless till used; as soon as you use it, it's no longer potential enegy, it's work being done. Pressure is the potential to do work, a measure of the ability of air to expand, but it is not the work itself. Take atmospheric pressure, for example. Atmosphere is about 14.7 psi higher in pressure than total vacuum or absolute 0 psi, but under normal conditions it can do no work. Why not? It doesn't have the ability to expand, because there is no lower-pressure body of air for it to expand into. Therefore, we usually exile all pressure below atmospheric to an unmeasured status since it's of no use (despite its potential energy), and we measure the pressure of air tanks with gauges that refer to atmospheric pressure as zero pressure, even though it's not true; gauge pressure is <u>usable</u> pressure. Pressure is only a measure of how much expansion is going to take place when you open the valve on the tank; pressure doesn't do the piston-pushing, it only measures the extent to which piston-pushing could take place.

Then what does push the piston? This is a chapter on thermodynamics, and heat energy is what we're talking about. Thermodynamics is the study of heat-energy and its transformations. To design an engine that runs on compressed air, and especially in order to arrange for that compressed air to deliver power derived from the sun instead of from industry, it is necessary to know why compressed air pushes pistons! I have learned, (by reading old textbooks, since modern compressed air books completely ignore the whole

issue), that **heat** pushes the piston in an air motor, transforming itself into mechanical energy. Heat-energy makes piston-pushing possible; expansion is the thermodynamic event that converts heat into mechanical motion (pushes the piston), and pressure is just a measurement, relative to the backpressure on the piston, of how much of the heat energy is available for use. When we study absolute temperature, absolute pressure, and internal energy, we'll see that air contains lots of heat that is normally unavailable for use; thus the need for a measurement device--pressure--that tells us how much of this total heat content is available for use. The benefit of compressed air is related to the fact that huge amounts of this normally unavailable heat energy can be liberated for use by purposeful manipulations with rather ordinary hardware.

I first referred to pressure as a result of preventing expansion by trapping air when heat is added to it. The term "expansion" is used in different contexts in pneumatics; all of these contexts describe the acceleration of air molecules by the liberation of heat energy. When you heat air that is free to expand, its molecules move farther apart, the volume of the body of air expands, the body of air takes up more space. That is the first context. When you heat air that's trapped in a closed space so that it can't expand, its desire to expand (pressure) goes up, and when you stop adding heat to the air, its pressure soon drops with its temperature till it has no more desire to expand than what it started out with. In this context there is no expansion.

In another context, trap a body of air in a closed space, and then shrink that space, so that when you're done, the body of air takes up less space than it used to. This is what a compressor does. We know that when you directly heat molecules, they speed away from each other, bump into each other, and therefore their temperature goes up due to friction. In the process of compression, the same phenomena take place for different reasons. Instead of heating air to make it expand so the molecules rub up against each other and get hot, we're compressing air, converting the mechanical work of the compressor into heat energy. The molecules want to be atmospherically close together, no closer. Pushing them together into a closed place makes them rub up against each other, heat up due to friction, and therefore want to expand. This desire to expand is measured as temperature and pressure, which both increase during direct heating or compression. The work that the compressor does in mechanically slamming molecules against each other changes into heat through the process of friction. Friction is the waste of energy, generally to be avoided. Direct heating raises temperature due to increased molecular motion, and compression heating raises temperature due to decreased space for molecules to move in. Air molecules want to be in their natural proximity to each other, which is defined by their ambient conditions, that is, atmospheric pressure and temperature. To force them closer is to buck up against equilibrium, a friction-producing act.

One context in which the term "expansion" is used is the result of compression. Once air has been pushed into a tank and thereby heated, it wants to expand. The temperature and pressure go up together, because not only have the molecules been crammed together with less room to move and therefore a rise in temperature; also, the walls of the compression cylinder, then the tank, prevent the expansion that wants to happen, which causes the rise in pressure. If the hot compressed air were immediately

used to push an engine cylinder, the same work just done in compression would be gotten back in expansion, not counting losses.

The special context of expansion that I'm trying to get to is this: what if the compressed air in the tank is allowed to cool back to the temperature of its surroundings? All the compression heat—which was caused by air friction, and not by volume reduction as most engineers assume—has dissipated, but there's still pressure in the tank. That means it still has the ability to expand. Why? Here is a hint of the great secret benefit of compressed air. Compressed air in a tank, cooled to ambient temperature, has the ability to convert, through expansion, the heat that was already in it before it was compressed, into mechanical energy. As proof, I remind you that compressed air that starts out at ambient temperature gets very cold when it pushes a piston. So the trick here is that the useless heat contained in atmospheric air has been put in position to do work after all. The hardware end of taking full advantage of this phenomenon is wrapped up in finding a way to get ordinary atmosphere into a full tank of compressed air without a compressor. This discussion will be taken up in other chapters.

To summarize the various contexts in which the term "expansion" is used:

1. direct heating of air that is free to expand; spontaneous expansion allows no net rise in temperature or pressure;
2. direct heating of trapped air with no expansion; temporary rise in temperature and pressure; when heat dissipates, pressure is also gone, along with the potential for expansion;
3. compression heating of trapped air followed by immediate expansion; when pressure is back to baseline, temperature has also fallen to baseline; work gained in expansion is equivalent to work expended in compression, minus losses;
4. compression heating of trapped air followed by dissipation of all compression heat; the pressure of the trapped body of air is still elevated; expansion now cools the air to below baseline, because the ambient heat that was in the air before it was compressed was made available for expansion by first letting compression heat dissipate.

This fourth context of expansion is the normal way that compressed air is used, and is of great interest to us. Although the air in the tank has cooled to the temperature of its surroundings before we allow it to expand, its pressure is still above atmospheric. Getting back to the definition of pressure given above—the ability to expand because of heat content—it is proven that expansion is done by heat, not pressure, by two observations: first, the temperature of the air goes down when expansion takes place, proving that heat energy has been used in expansion, and second, there is no other explanation for the existence of pressure in the tank after all the compression heat has dissipated; pressure MUST BE an indicator of the existence of an underlying energy source, because all the work done by the compressor is wasted as compression heat. This is a fact straight out of the textbooks, although not every textbook writer goes this deeply into the facts.

The Nature Of Compressed Air As An Energy Carrier:
WHAT IT IS AND WHY

1. THE ENERGY IN A GIVEN VOLUME AT A GIVEN PRESSURE

WHAT IT IS

PV, pressure × volume, absolute pressure in lbs. per sq. ft. × volume of air in cu. ft.; pressure in lbs/ft^2 = psi × 144; absolute pressure (psia) = gauge pressure (psig) + 14.7; absolute pressure in lbs/sq^2 = 144(psig + 14.7)

PV = energy in air

= a general statement about energy invested to get the air into its present state

= a general statement about what can be gotten out of the air

WHY?

Pressure is a component of force, and force is a component of work, and work is equivalent to energy.

Pressure × the surface area upon which the pressure is applied is force. Example: a wind pressure of 10 lbs/ft^2 blowing against a wall of 300 ft^2 = 10 × 300 = 3000 pounds of force.

Force × the distance through which the force acts is work. Example: a hydraulic ram lifts a 2000 lb. car 8 ft. into the air. 2000 × 8 = 16,000 ft. lbs. of work.

In the case of PV = work: Volume. is length × height × width. Height × width is surface area. Surface area × length is volume, therefore,

pressure × area × length = force × distance = work = PV.

2. **BOYLE'S LAW** *GOVERNS PRESSURE AND VOLUME CHANGES AT CONSTANT TEMPERATURE*

WHAT IT IS

$P_1V_1 = P_2V_2$ at constant temperature

PV is constant at constant temperature

Pressure and volume vary inversely to each other when temperature doesn't change.

$$\frac{p_2}{p_1} = \frac{v_1}{v_2}$$

Remember to use consistent units for PV; psi must be converted to lbs/ft^2 when volume is in ft^3; psi $\times$ 144 = lbs/ft^2

"PV = constant" defines Boyle's law which describes isothermal processes, in which there is no net temperature change; $(PV)^1$ is the same thing; non-isothermal processes (where temperature changes accompany PV changes) are described by $(PV)^n$. The exponent n is explained in the section below on ratio of specific heats.

WHY?

Boyle's Law is fairly obvious; it boils down to PV = PV or, "PV is constant for a given body of air, when there's no net gain or loss of heat." The explanation below describes the isothermal processes partly by describing non-isothermal processes. Of the non-isothermal processes, the only ones that concern this basic discussion are adiabatic compression and expansion, the processes described below which are characterized by no heat exchange with the surroundings.

Consider a 1 ft^3 volume of air at a pressure of 100 psia. If you stuff that air into half its original volume without changing its temperature, the same number of molecules taking up half the space will be exactly twice as eager to expand as when they were at 100 psia. $P_1V_1 = (100 \text{ psia} \times 144) \times 1 \text{ ft}^3 = 14{,}400$ ft. lbs.; $P_2V_2 = (200 \text{ psia} \times 144) \times \frac{1}{2} \text{ ft}^3 = 14{,}400$ ft.lbs.; therefore, $P_1V_1 = P_2V_2$.

Normally when you push air molecules together, the friction of rubbing the air molecules together causes compression heating. The heat causes the air to want to expand, so its pressure goes up during compression, not just because you're shoving it into a smaller volume out of which it wants to re-expand, but also because this shoving in itself raises the air's temperature, which makes it want to expand even more due to heat. Boyle's Law describes a simplified condition called "isothermal compression" in which the compression heating either doesn't take place or the heat is removed from the air as fast as it's generated. Although it's fairly impracticable to compress air with no temperature rise, you can imagine coming close to isothermal conditions by compressing so slowly that heat exchangers have time to remove all heat before it has a chance to increase the effective volume of air to be compressed. Thus in isothermal compression, the extra "volume" of air caused by compression heating is removed before work is invested in compressing that volume. Isothermal compression is aimed for by multistage compressors which cool air before, during, and/or after each stage of compression, so there is in effect less volume to compress. The problem with compressing hot air is that the compressor thinks there's more air in its cylinders to squeeze together than there really is, because the air that really is in its cylinders is trying to expand while it's being compressed, thus resisting the work being done to compress it. So the compressor has to do more compression work to counteract this extra expansion, to arrive at a given pressure. Then the air sits in the tank

and cools off, and all that extra volume, which only existed because of transient heat buildup, is gone and the tank pressure drops off to what it would have been if heat had been removed before extra work had been invested in compressing air volume that didn't exist. The work done to fight expansion due to heat is all wasted, with no compressed air to show for it in the end.

Because of this, and because writers on pneumatics always assume that compression heat will not be saved for re-use, isothermal compression, which is mathematically described by Boyle's Law, is considered the most efficient way to compress air. This isn't always necessarily true in every circumstance, but you must understand how textbook writers think in order to use their excellent charts. I am not changing any of the facts or contradicting anything written in any textbook; I'm presenting an expanded set of possibilities offered by a wider perspective on standard pneumatics facts.

The other facet of Boyle's Law is isothermal expansion. This is an expansion process with no temperature change. Imagine a piston in an air engine with compressed air metered to it so slowly that when it tries to drop in temperature, since piston-pushing in an air engine is done at the expense of the air's internal energy or heat content, ambient heat is absorbed through the cylinder walls from the surroundings to keep the air temperature constant. As in compression, isothermal conditions are approached by spreading the expansion process out over multiple stages; the air has more time to absorb heat from its surroundings before, during and/or after each stage in the multistage expansion engine.

In the absence of isothermal conditions, expansion is, from some perspectives, less productive since the expanding air continuously gets colder and shrinks due to conversion of internal energy (heat), into mechanical energy (engine work). Air volume also shrinks when it enters the cylinder and hits the cold metal, so effectively there is less compressed air to do work. Under isothermal conditions as defined by Boyle's Law, if a body of compressed air expands to twice its original volume, its pressure goes down exactly half. Under real conditions, less work is done because of the loss of effective volume, and the final pressure after a given expansion is less.

As before, an expanded perspective will point out the hidden advantages of what appears to be the disadvantage of allowing air to give up its internal energy in expansion.

3. CHARLES' LAW *GOVERNS CHANGES OF PRESSURE OR VOLUME WHEN TEMPERATURE CHANGES*

WHAT IT IS

*At a constant volume, the absolute temperature and absolute pressure of a given weight of air change in proportion to each other: $\frac{P_1}{P_2} = \frac{T_1}{T_2}$.

**At constant pressure, the absolute temperature and volume of a given weight of air change in proportion to each other: $\frac{V_1}{V_2} = \frac{T_1}{T_2}$.

WHY?

While Boyle's Law describes how pressure and volume would change in relation to each other if temperature were held constant, Charles' Law similarly describes how temperature and pressure would change together if volume were held constant, and how temperature and volume would change together if pressure were held constant. Since there are three main variables changing all at once, we learn about pneumatic theory the easy way by isolating the changes from each other, and looking at one relationship at a time. When this all makes sense, we will move on, and combine all three variables to see how they all change together.

The fact of nature that stands behind Charles' Law is absolute zero. Absolute zero is a state where matter contains no heat, therefore ceases to occupy space and has no pressure and no energy. Absolute zero is about 460° below 0° F.; absolute temperature is the temperature in °F. plus 460. By observing the proportion of the changes of volume and pressure that occur in a substance when the substance is heated or cooled, the point on the temperature scale where matter would cease to occupy space or have pressure has been deduced. For example, air at an absolute temperature of 492°, if kept at a constant pressure and cooled 1°, would shrink by $\frac{1}{492}$ of its original volume. The number of degrees that a gas would have to be heated to increase or decrease its volume 100%, at constant pressure, is the same as the number of degrees between the gas' original temperature and absolute zero. $\frac{1}{492}$ is the *coefficient of expansion* of a gas at 32° F. At a different temperature, or on a different temperature scale such as Celsius, the coefficient of expansion would be different; absolute zero is the constant quantity from which the other quantities are derived.

One reason that ambient heat is not recognized as a significant source of solar energy--although the everyday performance of ordinary heat pumps proves the contrary--is that we measure temperature from an elevated point on the scale(such as 0° F. or 0° C.) instead of measuring from absolute zero. If we were looking at thermometers that read 550° Abs. instead of 90° F., someone would have though of putting all that solar energy to use a long time ago.

As noted above in my description of Boyle's Law, the extra or missing effective volume due to heating-expansion or cooling-contraction in adiabatic processes is of utmost importance in predicting what will really happen in air undergoing changes in its condition. It is Charles' Law, based on the fact of absolute zero and the coefficient of expansion derived from absolute zero, that help us know how much of this expansion and contraction will take place with a given temperature change.

An equivalent description of Charles' Law, known as the Second Law of Perfect Gases: a perfect gas is a condition in which increments of expansion and contraction are

equal throughout the whole range of operation for both volume and temperature. Air is close enough to being a perfect gas in the normal range of operation that Charles' Law may be used with accuracy.

*Charles noted this phenomenon in 1787, but never published it.
**Dalton published this phenomenon in 1801. Gay Lussac published the same phenomenon independently of Dalton in 1802, giving Charles credit for the discovery.

4. THE **COMBINED GAS LAW** *COMPLETES THE PICTURE OF PRESSURE-, VOLUME-, AND TEMPERATURE-CHANGE RELATIONSHIPS*

WHAT IT IS

The Combined Gas Law is as follows:

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2},$$

or, solving for one variable; final absolute pressure, for example:

$$P_2 = \frac{P_1V_1T_2}{V_2T_1}.$$

The other variables can be isolated in the same way and solved for, using basic algebra as was done in the example above.

The Combined Gas Law describes the behavior of a certain weight of air undergoing simultaneous changes in its three main variables: pressure, volume, and temperature. This fits real conditions better than using Boyle's or Charles' Law alone, since in nature there is seldom a constant pressure, volume, or temperature when one of the other variables changes.

WHY?

Gas Law for constant temperature: $P_1V_1 = P_2V_2$.

Gas Law for constant volume: $P_1T_2 = P_2T_1$.

Gas Law for constant pressure: $V_1T_2 = V_2T_1$.

The three gas laws are combined by multiplying the three formulas together:

$$P_1V_1 \times P_1T_2 \times V_1T_2 = P_2V_2 \times P_2T_1 \times V_2T_1 ,$$

which simplifies to: $$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}.$$

5. THE COMBINED GAS LAW GIVES THE GAS CONSTANT

WHAT IT IS

For any given weight of air, $\frac{PV}{T} = k$, a constant.

WHY?

When lost in the forest of simultaneously changing variables, it's of great comfort to discover that the quotient of the combined gas law never changes for a given weight of air. This knowledge is extremely useful; if you know the pressure, volume, and temperature of a given weight of air at an initial condition, and you know the final volume and pressure (for example), you can easily find the final temperature. Likewise, any of the three variables—pressure, volume and temperature—can be solved for, if the other two variables of the final condition are known. Or, if only one of the variables of the final condition is known, knowing the gas constant for the given weight of air still makes it possible to find a set of coordinates for the other two variables.

Example A, two variables of the final condition known:

Initial absolute pressure, $P_1 = 14.7$ psia $\times 144 = 2116.8$ lbs/ft^2

Initial volume, $V_1 = 1$ ft^3

Initial temperature, $T_1 = 32°$ F. $= 32 + 460 = 492°$ Abs.

Gas constant $= \frac{2116.8 \times 1}{492} = 4.3 = k$

If you want to know what the final temperature of the gas would be at, for example, a final pressure of 214.7 psia and a final volume of .1 ft^3:

Final absolute pressure, $P_2 = 214.7 \times 144 = 30{,}916.8$ lbs/ft^2

Final volume, $V_2 = .1$ ft^3

Final temperature, $T_2 = \frac{P_2V_2}{k} = \frac{30{,}916.8 \times .1}{4.3} = 719°$ Abs.;

719° Abs. - 460 = 259° F.

Example B, one variable of the final condition known:

Solving for the same weight of air as Example A, same initial values; k = 4.3

If we know that the final temperature is 60° F. (520° Abs.), find a set of solutions for the final pressure and final volume:

$$4.3 = \frac{P_2V_2}{520}$$

$$P_2V_2 = 4.3 \times 520 = 2236$$

$$P_2 = \frac{2236}{V_2};\ V_2 = \frac{2236}{P_2}$$

To find what the final volume will be if the final pressure is 114.7 psia, $V_2 = \dfrac{2236}{114.7 \times 144} = \dfrac{2236}{16{,}516.8} = .135\ \text{ft}^3$

If a final volume of .085 ft^3 is preferred, the final pressure can be found: $P_2 = \dfrac{2236}{.085} = 26{,}305.882; \dfrac{26{,}305.882}{144} = 182.68\ \text{psia}$

These are examples of how much can be done with just a little knowledge of pneumatic theory; we will learn more concepts below, some of which tie back in to the gas constant to show its real value. See *difference of specific heats.*

One more refinement can be made in our use of the gas constant itself. As shown up to this point, the gas constant is general for any given weight of a certain gas. To come up with a number that is specific to air, the conditions of one pound of atmospheric air at sea-level and 32° F. are standard. Knowing that one ft^3 of air at these conditions weighs 0.08071 lb., and knowing the more accurate value of absolute zero to be -459.6° F., the value of the gas constant specific to air is found:

$$k = \frac{PV}{T} = \frac{(14.7 \times 144)(1)}{(459.6 + 32)} = \frac{2116.8}{491.6} = 4.306;$$

$$k_G = \frac{4.306}{.08071} = 53.35$$

$53.35 = k_G$ = the gas constant specific to one pound of air at the standard condition. For examples of its use, see the next section. The key to understanding the concept is that k_G = the $\dfrac{PV}{T}$ condition for one pound of air at standard condition, and this value stays constant as the pressure, volume, and temperature of the one pound of air change. So if you alter this constant one-pound-value for air (53.35) by introducing the actual properties of a certain body of air, the number 53.35 acts like a mold or jig to make the new numbers conform to the properties of air which are dictated by nature. If any gas other than air were under consideration, we would use a different constant that works specifically for that gas.

While the Combined Gas Law and the gas constant derived from it can give us a lot of information about how air behaves, the derivation will be taken another step below, in the section on the General Gas Law.

6. INCLUDING THE WEIGHT OF AIR WITH THE COMBINED GAS LAW COMPLETES THE **GENERAL GAS LAW**

WHAT IT IS

The General Gas Law formulas are as follows:

$$PV = Wk_GT \quad \text{pressure and volume}$$

$$P = \frac{Wk_GT}{V} \quad \text{lb/ft}^2 \text{ abs.}$$

$$V = \frac{Wk_GT}{P} \quad \text{ft}^3$$

$$T = \frac{PV}{Wk_G} \quad {}^\circ \text{ F. abs.}$$

$$W = \frac{PV}{k_GT} \quad \text{lb.}$$

$$k_G = \frac{PV}{WT} \quad \text{gas constant}$$

$$D = \frac{W}{V} = \frac{P}{k_GT} \qquad \text{density, lb/ft}^3$$

WHY

The General Gas Law is a simple mathematical summation of the relations between all the things about a body of still (static) air that can vary: absolute pressure, volume, absolute temperature, and weight. Pressure can be changed by changing any of the other variables; volume can be changed by expansion or compression; temperature also changes with any variation; and weight changes with the addition or subtraction of air molecules to the volume of air. Note: volume is just the space air takes up; weight is how much air is in the space, a set number of molecules for a given weight; density is a combination of volume and weight, that is, weight per unit volume.

The General Gas Law formulas are the everyday tools a pneumatic designer uses to juggle concepts involving the constantly changing conditions of a group of invisible molecules. You can’t run out in the garage and build an air car engine to see if your guesses are going to work out, and there’s no reason to re-invent pneumatic engineering; you just have to understand it in a wider scope than the professionals in industry who only design air motors for portability and convenience. Fortunately, the concepts you need to master are simple, if you take them one at a time.

We are considering four properties of air: pressure, volume, temperature and weight. I will give examples of the two main types of problems that can be solved with the General Gas Law. **A.** If three of these properties are known about a certain condition of a given quantity of air, the formulas above can be used to find the fourth property. **B**. If three of the properties are known for the initial condition of a given quantity of air, and two of these values stay the same for the final condition of the air, and the value of one of the changed values is known, then, the final value of the other changed property can be found.

Example A, three properties known & the fourth solved, for a given condition:

The air in your car's main drive tank can be assumed to be at ambient temperature since the car has sat idle for some time. The temperature is 73° F., which you convert to absolute temperature, 73 + 459.6 = 532.6° abs. The tank's gauge reads 160 psi, which you convert to absolute pressure in lbs/ft^2, 144(160 + 14.7) = 25,156.8 lbs/ft^2. You know that the tank is exactly two feet long, and its inner diameter is seven inches. Using the standard calculation for determining the volume of a cylinder, you find that the tank's volume is 0.5345 ft^3. To find the weight of the air in the tank,

$$W = \frac{PV}{k_G T} = \frac{25{,}156.8 \times .5345}{53.35 \times 532.6} = .47 \text{ lb of air.}$$

Example B, three of four initial values known; two values change for final condition and two are constant; one of the changed values is known and one must be found:

You have six small tanks about the size of scuba tanks, and you want to look into using them as the high pressure storage tanks in your air car. You decide that you don't want the air in the tanks to weigh over 50 pounds each when full, and you need to know how much pressure will be in them when their empty weight is increased 50 pounds by their contents. The initial condition is defined by the inside volume of the scuba tank, which you estimate, based on a scuba tank manufacturer's catalog, to be 475 in^3, and then divide by the conversion factor to get 475 ÷ 1728 = 0.275 ft^3; the tank's empty pressure, which is atmospheric pressure or 14.7 psia × 144 = 2116.8 lbs/ft^2; and the ambient temperature, which today is 107° F. + 459.6 = 566.6° abs. The first step is to find the weight of the atmosphere already contained in the empty tank:

$$W = \frac{PV}{k_G T} = \frac{2116.8 \times .275}{53.35 \times 566.6} = .019 \text{ lb.}$$

Now that you know the values for all four properties of the initial condition, the next step is to find the unknown pressure for the final condition:

$$P = \frac{Wk_G T}{V} = \frac{50 \times 53.35 \times 566.6}{.275} = 5{,}496{,}020 \text{ lbs/ft}^2;$$

$(5{,}496{,}020 \div 144) - 14.7 = 38{,}167$ psig.

The result of your inquiry is that the air in the tank will not weigh 50 lbs. unless you somehow manage to fill it to 38,167 psi.

The General Gas Law formulas given above are the final derivations and combinations of the four variables in compressed air calculations. Other important concepts are given below, which not only prove the validity of those ideas already presented, but present some revolutionary ideas about compressed air as a source of practically unlimited quantities of solar energy. The solar-pneumatic issue has been brushed over, swept under the rug, and outright ignored by other textbook writers, and it's time the whole truth came out in the open. So keep reading!

7. THE TOTAL HEAT ADDED TO OR SUBTRACTED FROM AIR PRODUCES EITHER OR BOTH OF TWO EFFECTS: **INTERNAL AND EXTERNAL WORK**

WHAT IT IS

The *Specific Heat* of a substance is the quantity of heat energy, measured in BTU's, that it takes to raise the temperature of 1 lb. of that substance 1° F. There are different specific heats for different types of processes, and these are defined by considerations related to the three types of heat-energy-investment listed below:

Internal Work is the work done by heat energy in the raising of the temperature of that heat energy's host substance; that is, increasing its internal energy.

External Work is the work done by heat energy in the expansion of that heat energy's host substance against an external resistance.

The only other effect of adding heat energy to a substance is *Change-of-State Work*. An example is the work done in freezing water, when BTU's must be invested in pushing the liquid over the hump to the solid state; these BTU's, while needed to force the change-of-state, do not lower the temperature of the water. Since we aren't concerned with producing liquid air, or with the low temperature ranges at which air's change-of-state occurs, no energy investment in change-of-state needs to be considered in the design of air engines.

WHY?

The total heat-energy investment is divided between internal work and external work. Where this division occurs depends on the rate at which expansion is allowed to take place. Imagine a piston whose rod you can restrain with a handle. We'll look at three conditions: initial, intermediate, and final:

Initially, heat is added to the air in the cylinder, with the piston held in place.

In the intermediate condition, The heat added in the initial condition has all been used to raise the temperature of the air; since the piston is fixed in place, the air can't expand to do external work. In this state, the pressure in the cylinder will have also gone up.

The final condition begins when the temperature in the cylinder has reached x°. At this point, you continue adding heat to the cylinder, but instead of holding the piston stationary, allow it to extend only fast enough to keep the temperature in the cylinder at x°. After a period of time, the volume of the air will have increased because of the added heat, and the pressure in the cylinder will have gone down because of this expansion. But the temperature of the air has remained the same, so all of the heat expended has been invested in external work in this condition, and none has gone into raising the temperature of the air.

Getting Specific About Heat

The *specific heat* of air is one of the most important quantities needed in order to understand how energy expresses itself as heat in a compressed air medium. If heat were just heat, it would be much simpler, but it's not as simple as "heat pushes pistons." Several important factors influence each other when working with air—BTUs, pressure, volume, and temperature, for example—and the practical use of these intertwining relationships revolves around a solid understanding of the specific heat of air, which is the amount of energy, measured in BTUs, that you need in order to raise the temperature of a pound of air by one degree Fahrenheit. And because pressure, volume, and temperature can all change when one of them changes, there is more than one kind of specific heat, depending on conditions. The concept of specific heat is one of the main building blocks in learning how to answer the question, "How much energy does it take to compress air, and how much work can that compressed air do?" and more importantly, "WHY?!?"

Within the range of temperatures in practical use, the average specific heat of air at *constant pressure* (C_p) is 0.2375 BTU. *Constant pressure* here means that while the body of air is being heated, it's free to expand just enough so that it doesn't build up pressure. You could imagine a piston extending against the constant resistance of atmospheric backpressure. To raise the temperature of the air in the cylinder by 1° F. would require .2375 BTU per pound of air, as long as the heat is added to the air just fast enough to keep the pressure from building up. The more expansion is allowed in relation to the heat being added and the weight of the air being heated, the greater the specific heat, because more external work is being done at the expense of added heat. The "real" specific heat of

air is the specific heat at constant volume, where no expansion is allowed, for example in a cylinder whose piston is overpowered by its load, or in a tank with fixed walls where expansion is impossible. Progressing in stages from the specific heat at constant volume, consider first the condition in which some expansion is allowed, therefore some pressure is building up, but not as much as if no expansion were allowed whatsoever. The specific heat at this condition will therefore be greater than the specific heat at constant volume, since some energy is being invested in doing external work, but less than the specific heat at constant pressure, since not enough work is being done by expansion to prevent the buildup of pressure altogether. Next consider the specific heat at constant pressure, which is the condition when just enough work is being done by expansion to keep the pressure constant at the initial value. To continue in this line of thinking, consider the condition in which there is so little resistance to expansion in relation to the amount of heat being added to the air that, not only is the pressure not going up while heat is being added; there is so much expansion taking place that the pressure is actually going down while heat is being added. Of course, the expansion will stop when the air in the cylinder expands to match the resistance against which it is expanding.

To restate this line of thinking, imagine a piston that at first won't move because the heat-energy being expended to raise the temperature of the air in the cylinder is less than the work-energy resisting the piston's motion. The energy input at this point is the specific heat at constant volume, since temperature is going up but no work is being done externally. Then the pressure of the air in the cylinder reaches the point where it has increased enough to start moving the piston a little bit; now the specific heat has increased a little. Once the inertia of the moving parts has been overcome and pressure continues to build up with added heat and rising temperatures, there comes a point where expansion proceeds at a rate just fast enough to keep the air in the cylinder at a constant pressure; the specific heat is then at the value we call constant pressure. Then if the resistance goes down, the energy being added to the cylinder is of greater magnitude than what is needed to maintain equilibrium against the resistance to expansion, and pressure falls in the cylinder as heat is still being added.

During all air-heating processes, the amount of heat that is responsible for raising the air's temperature is the same: the specific heat of air at constant volume is .1689 BTUs per pound of air per ° F. of temperature change. Note, however, that if expansion is allowed to take place so quickly that the temperature remains constant even while heat is being added, then the specific heat at constant volume doesn't apply, since all heat being added is going directly into expansion.

It has been determined experimentally that in expanding against an external resistance, air that maintains a constant pressure while being heated does work equivalent to.0686 BTU per pound of air per ° F. temperature change. In other words, for every .2375 BTU's of heat added to a pound of air which is expanding just enough to stay at a constant pressure, .0686 of the total BTU investment is doing external work. It has been deduced further that if this work produced by the expanding air (.0686 BTU) is subtracted from the total work done in heating the air (.2375 BTU), the remainder, .1689 BTU, is the specific heat of air at *constant volume* (C_v). It would take .1689 BTU of heat to raise the temperature of one pound of air by 1° F. if the volume of the air were kept constant (no

expansion allowed). The specific heat at constant volume has been deduced as described above, rather than discovered by experiment.

Later we will discuss the exact use for the specific heats of air, including the ratios of specific heats and the difference between specific heats. But first, I will raise and then answer the most important theoretical question in the field of solar pneumatics:

Why Does The Value .0686 × 778 (The Conversion Factor From BTUs To Ft-lbs) = 53.3, The Energy Value Of Air At Atmospheric Conditions?

What makes this question so important?

Since I'm making what most engineers would consider to be an extraordinary claim—that compressed air should be viewed and used as a form of solar energy—I feel an obligation to demonstrate point-by-point that I understand standard pneumatic engineering theory well enough to explain it to my fellow laymen, who will take an interest in my ideas when engineers turn away and scoff. I also feel an obligation to prove every claim I make by the use of standard engineering fact, and not by conjecture or by theories of my own. I'm a researcher, or writer, not an engineer or scientist. I feel no sense of duty to convince anybody of anything, but if I'm going to say something about compressed air, I want my statements to be not only true, but based on what has long been published in standard textbooks and established as scientific fact.

In composing this essay on the nature of compressed air, I was forced to sift through numerous engineering books on pneumatics one idea at a time, to find the easiest way to explain each concept to my own understanding, so that I could hope to get these concepts across to others, most of whom have little or no formal training in engineering science. And to make my explanation palatable to my own skeptical nature, I made it my goal to not only understand each concept, but to find out from what other more basic concept each secondary concept was built. In this pursuit I have built a chain of logic that begins with a few undeniable laws of nature, and then forms secondary concepts as combinations and extrapolations of these few basic elements. I have found only four truly basic facts about compressed air theory, or laws, from which every other idea in this book and other compressed air textbooks is built: Boyle's Law, Charles' Law, the Specific Heat of Air, and the Energy of Atmosphere.

When I put this chain of logic into its natural order, depending on which idea must come first in order for another idea to be valid, and which idea must be combined with which other idea to show that a third idea results from good logic and not guesswork, I found a coincidence that I was forced to explain to myself; I don't like coincidences when trying to explain something in black-and-white terms. It turns out that the difference in specific heats, which was demonstrated by experiment, is the same quantity as the gas constant for air, which was demonstrated by pure mathematical theory. The point is that the two concepts are equal, but started out from two different sources of information. This is not circular thinking such as when the dictionary uses "blossom" to define "flower," and

"flower" to define "blossom." This is a case of two seemingly unrelated basic facts of nature leading through two separate chains of secondary facts into the common meeting ground of one quantity with two names and two equally true derivations.

While you may not share my enthusiasm for the phenomenon of a known and mundane fact being provable in two entirely different ways, you must admit that the unbroken circle of logic which I am presenting as an explanation for the solar nature of compressed air's energy source is nothing more than the big picture comprising the little facts that have been use routinely for a hundred years to design ordinary pneumatic motors, engines, compressors and other appliances. Nowhere in this book do I depart from standard theory. In fact, my claim has been made, piecemeal, by engineer-writers, the totality of it scattered from book to book and from author to author. My excitement at being able to bring compressed air theory from its basic laws, through full circle to a total agreement of theory and experiment, is explained by the fact that now I can use the completeness of my introduction to pneumatics as a basis for confidence that my readers will not only know what I'm trying to say and why; they will also feel that they have every reason to look seriously at my claim regarding the solar pneumatic issue, and look into the implications.

I will now get on with the most important fact in this book, which will also be proved with a multi-source chain of logic meeting itself full circle at an indisputable, though rarely mentioned fact straight out of the engineering books:

All Work Expended In Compressing Air Is Converted Into Heat And Is Lost To The Surroundings.

The obvious implication of this statement, which is easy to prove mathematically using the standard engineering formulas used everday with compressed air, is that ***the source of compressed air's ability to do work is the heat that was put there by the sun***.

This concept is of such vast importance that I will not attempt to paraphrase it; I will reprint here the relevant sections of ordinary compressed air textbooks, and you can see the mathematical proof and judge for yourself. Keep in mind that the U.S. Patent Office gives patents to designers of self-fueling air engines all the time. The patent office will not grant patents for perpetual motion machines that have no energy source, and although neither the patent office nor the patentees are forthcoming with the secret energy source that make these machines patentable, when you see how many of these patents exist, you must know that something is up. But I have no secret to protect and no patent to hoard for myself, so here's the documentation proving the Solar-Pneumatic Connection.

Documentation From Engineering Texts Proving That All Compression Work Is Lost As Heat

Q: So where does the usable energy in compressed air come from?
A: It comes from the sun!

CROFT

In compressing the gas...All of this work (assuming a frictionless piston and no loss of heat) is converted into heat in the compressed gas. Thereby the temperature of the gas is increased. When the gas is permitted to expand, it does work....Its heat content and temperature are thereby decreased accordingly.

(Practical Heat, Terrell Croft, New York: McGraw-Hill, 1923, p. 189.)

WIGHTMAN

Phenomena of Compression. *Thermodynamics* is the science of the relation between heat and energy. It is based on two fundamental laws, only the first of which has a bearing on the discussion of compressed air.

The First Law of Thermodynamics states that *where heat is converted into mechanical energy, or mechanical energy is converted into heat, the quantity of heat is exactly equivalent to the amount of mechanical energy.*

This law demands that when work is done upon a volume of air in compressing it from a lower to a higher pressure, a quantity of heat must be developed exactly equivalent to the energy expended in compression.

In other words, when a volume of air is compressed to a higher pressure, all the work done upon that air volume is converted into heat; and that heat acts to increase the temperature of the air volume, whether the process of compression be slow or fast.

(Compressed Air, Lucius I. Wightman, Chicago: American Technical Society, 1914, p. 6.)

SHONE

Availability

By the First Law of Thermodynamics and the principle of the Conservation of Energy, a complete accounting can be made of all relevant forms of energy entering, leaving, or contained in the compressed air....

However, the First Law, being simply an energy balance, provides little insight into the nature of the energy. For example, it takes no account of the capacity of energy to do useful work or of the inevitable dissipation, or degradation, of energy that accompanies all real processes. For this the Second Law of Thermodynamics is required.

The Second Law has an undeservedly poor reputation, mainly because of its apparent abstractions and its seeming irrelevance to practical problem solving. By combining the concepts of the First and Second Laws in a practical manner, energy may be classed as "available", "unavailable" or "degraded". Basic to this classification is the

concept that the purpose of energy is to do useful work. Energy that is capable of doing work is "available", that which cannot be employed for work is "unavailable" and the available energy that is eroded by friction or other dissipative processes is "degraded".

The work potential of compressed air is related to its initial and final states. For example, an air receiver charged to a high pressure clearly can provide more work if the air is expanded in a tool and exhausted to atmosphere than if it were exhausted at a higher pressure. It is equally clear that the work potential will be reduced if there is a pressure drop in the piping between the receiver and the tool.

Moreover, there is no doubt that the work potential will be wasted entirely it the air is allowed to expand directly to atmosphere.

The availability of compressed air

One of the sometimes puzzling aspects of compressed air, which is not explained by the First Law, is that in most cases the compressed air arriving at the tool contains no more energy than the atmospheric air.... for an isothermal (constant temperature) process the energy possessed by the air is unchanged....The heat equivalent of the input work is removed by cooling. It might appear therefore that compressed air has been obtained with no net expenditure of energy and that the eventual work is "free". This is manifestly incorrect, but it is a fact that in compressed air installations heat is removed from the air by cylinder jacket or internal cooling and by intercoolers, aftercoolers and by heat transfers from surfaces. The result is that shortly after compression storage and treatment, the compressed air has the same temperature as at the inlet to the compressor.

(The South African Mechanical Engineer, vol. 35, August 1985, "A different view of compressed air," Dick Shone.)

UNWIN

Case of Isothermal Compression.—It will be shown presently that the most economical compressor mechanically would be one in which heat is abstracted during compression, so that the compression is isothermal. In that case the effective work is...exactly equal to the absolute work of compression...But the heat abstracted during compression is equal to the same quantity. Hence the curious result is arrived at that in the most economical compression, the effective work of compression is entirely abstracted as heat and wasted. All the compression does is to put the air in a condition to do work in a motor at the expense of its intrinsic energy. In that way there is obtained an amount of work nearly equal to the work done in compression. But the work in the motor is not strictly the restoration of the energy expended in the compressor, but energy borrowed from the air....

(On the Development and Transmission of Power from Central Stations, William Cawthorne Unwin, London: Longmans, Green, 1894.)

FELLER

Important Fundamentals.--We know that *work* is a force overcoming resistance and is measured in foot-pounds. Energy, which exists in a number of forms, is the capacity to do work and can also be measured in foot-pounds. Heat, measured in Btu, is one form of energy. Power is the rate of doing work, the unit being the horsepower, or 33.000 ft-lb per min. Temperature is an indication of the direction in which heat will flow if it has the opportunity to do so. The internal energy of air depends on its temperature.

Work done in compressing air increases the air's internal energy and raises its temperature. As the compressor cylinder and piping are heat conductors, the whole of this heat soon dissipates to surrounding bodies and the air's internal energy gradually returns to its original value as the temperature falls to initial value.

Although 1 lb of air at 1,000 psi and atmospheric temperature has no more internal energy than 1 lb at atmospheric pressure and temperature, still the energy contained in the air under pressure is available for use because this air can expand, suffer a loss of pressure and temperature, and give up a portion of its internal energy. The greater the fall of pressure during expansion, the greater the fall in temperature and the greater the amount of internal energy available for use. The energy used in compressing air is not actually stored up in the air unless the heat of compression is retained. A portable compressor without cooling facilities furnishing air for immediate use approaches this condition. This internal energy depends on the temperature alone, and the energy that may be available for use depends on the fall of pressure and drop in temperature permissible.

(Air Compressors, Eugene W. F. Feller, New York: McGraw-Hill, 1944, p. 400-401.)

GRAHAM

It should be noted that the heat of compression, as already explained, represents work done upon the air for which there is usually no equivalent obtained, since the heat is all lost by radiation, before the air is used.

(Audel's Handy Book of Practical Electricity, Frank D. Graham, New York: Audel, 1942, p. 5607.)

BARNARD/ELLENWOOD/HIRSHFELD

It is interesting to note that, from the viewpoint of the conservation of energy, isothermal operation is not as advantageous as adiabatic. The object of using the air expansively is to utilize some of the internal energy of the working substance which enters the engine. If the expansion is isothermal no work can be done at the expense of such energy; on the contrary, heat equivalent in quantity to the work done during the expansion period must be supplied from an external source. With an adiabatic expansion, however, all of the work done during such an expansion will be at the expense of the *internal* energy of the gas.

The apparent discrepancy between these two cases is due to the fact that during the isothermal expansion it is assumed that the required amount of heat is supplied from the atmosphere, and that it costs nothing, and may, therefore, be freely used without decreasing the commercial efficiency of the process.

(Heat-Power Engineering, William N. Barnard, Frank O. Ellenwood, Clarence F. Hirshfeld, 3rd ed., New York: Wiley, 1926, p148.)

CHODZKO

There is nothing abnormal to an efficiency greater than 1, when reheating is used; this will occur (regardless of pipe and other friction) whenever the temperature of reheating is higher than the temperature of compression.

(Modern Machinery, January 1899, "The Two-Pipe System of Air Compression", A. E. Chodzko, p.11)

Effect Of Loss Of Heat, Generated During Compression, On The Ultimate Useful Energy Residing In A Given Quantity Of Compressed Air

117. By an accepted law of thermodynamics, work and heat are mutually convertible at the ratio of about 778 ft.-lb. of work for every B.T.U.

In Article 41a it was stated that the work expended in compressing air is all converted into heat. According to the law quoted, we should expect the compressed, and therefore heated, air to be capable of performing useful work, equal to the amount expended in compressing it. Neglecting friction in the air engine, this would actually be the case, if the compressed air could be used immediately after compression and before it has lost any of its heat.

If, on the other hand, the compressed air be allowed to cool down to the temperature which it possessed before compression, as happens in all compressed air installations, it would seem logical, by applying the same law quoted above, to reason as follows:

Since the work of compression is all converted into heat, the ability for doing useful work must have disappeared after all this heat has been abstracted.

In the following articles it will be shown:

a. That the work of compression is all converted into heat.

b. That, after all the heat of compression has been abstracted, there still remains in the compressed air a certain amount of energy for doing useful work.

c. That this is due to the energy residing in the air before compression.

a. Referring to Fig. 17, the total work of compressing adiabatically a volume V_1 cubic feet of free air from an absolute pressure P_1 to an absolute pressure P_2 is represented by the area MABR. Expressed in foot-pounds, it is equal to 144 times the numerical value of this area.

In Article 44 we found:

$$\text{Area MABR} = \frac{P_2V_2 - P_1V_1}{n-1} \tag{1}$$

therefore, total work of compression

$$W_1 = 144\frac{P_2V_2 - P_1V_1}{n-1} \text{ foot–pounds.} \tag{2}$$

Let P_1 = 14.7 lb. absolute pressure per square inch.

P_2 = 89.7 lb. absolute pressure per square inch.

= 75 lb. gage.

V_1 = 13.09 cu. ft. which is the volume of 1 lb. of free air at sea level and at 60° Fahr.

n= 1.406.

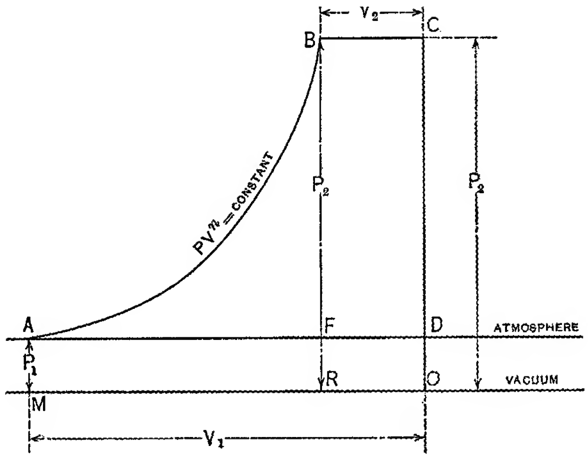


FIG. 17.

From equation (7), Article 41, deduce:

$$\frac{V_2}{V_1} = \left(\frac{P_1}{P_2}\right)^{\frac{1}{n}}$$

$$\text{whence} \quad V_2 = V_1\left(\frac{P_1}{P_2}\right)^{\frac{1}{n}} = 13.09\left(\frac{14.7}{89.7}\right)^{0.71} = 3.62 \text{ cu. ft.}$$

(3)

Substituting values in equation (2) we get:

$$W_1 = 144\frac{89.7 \times 3.62 - 14.7 \times 13.09}{0.406} = 47{,}000 \text{ ft.–lb.} \tag{4}$$

After the air has been compressed adiabatically to an absolute pressure P_2 its absolute temperature will be according to equation (11), Article 41:

$$T_2 = T_1\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}} = (60+461)\left(\frac{89.7}{14.7}\right)^{0.29} = 880° \text{ absolute} \tag{5}$$

$$= 419° \text{ Fahr.}$$

After compression, the original pound of air occupies a volume V_2 3.62 cu. ft. and has a temperature of 419° Fahr. which is (419 - 60) = 359 degrees more than its initial temperature.

Now, we can imagine a volume V_2 of air weighing 1 lb. to have a temperature of 60° Fahr. If we raise the temperature of this air by $(T_2 - T_1) = (880—561) = 359$ degrees without changing its volume, we heat under constant volume. The specific heat C_v of air in this case is 0.168 and the amount of heat put into this pound of air, expressed in B.T.U.'s is

$$C_v(T_2 - T_1) = 0.168 \times 359 = 60.3 \text{ B.T.U.'s.}$$

Expressed in foot-pounds it is:

$$K_v(T_2 - T_1) = 131.6 \times 359 = 47{,}000 \text{ ft.–lb.} \tag{6}$$

A comparison of equation (6) with (4) shows that the mechanical equivalent of the heat required to raise the temperature of 1 lb. of air from an absolute temperature T_1 to an absolute temperature T_2 is identical with the mechanical energy expended in compressing adiabatically 1 lb. of atmospheric air having an absolute temperature T_1 to a pressure which raises the temperature of the air to an absolute temperature T_2. In other words, the mechanical work of compressing air adiabatically is all converted into heat energy.

b. If we now allow this volume V_2 = 3.62 cu. ft. of compressed air, having a temperature of 419° Fahr., to cool down to initial temperature of 60° Fahr. under constant volume, its pressure will decrease to a pressure P_3, which we find from the formula:

$$P_3 = P_2 \frac{T_3}{T_2} = 89.7 \times \frac{521}{880} = 53.2 \text{ lb. absolute.}$$

The energy residing in this volume V_3 =3.62 cu. ft. of air for doing useful work in expanding adiabatically down from an absolute pressure of 53.2 lb. to atmospheric pressure is represented by the area *BCGF* in the diagram, Fig. 18, and expressed in foot-pounds it is 144 times the numerical value of this area. From article 110 we deduce:

$$\text{Area BCGF} = \frac{P_3V_2 - P_1V_1}{n-1}$$

Hence energy
$$W = 144\frac{P_3V_2 - P_1V_1}{n-1}$$

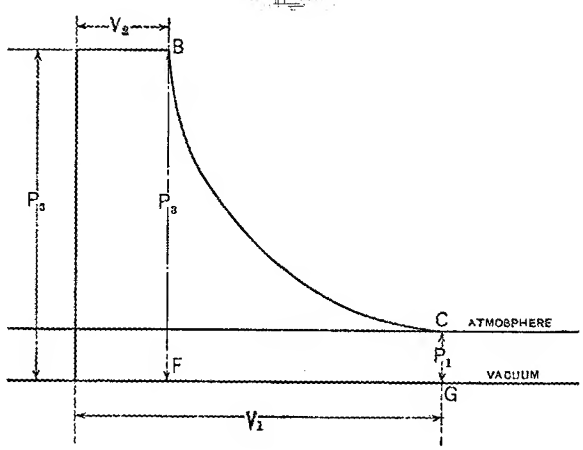


Fig. 18.

Applying it to the case in hand:

P_3 = 53.2 lb.absolute per sq.in.

V_2 = 3.62 cu.ft.

P_1 = 14.7 lb.per sq.in.

$$V_1 = V_2\left(\frac{P_3}{P_1}\right)^{\frac{1}{n}} = 3.62\left(\frac{53.2}{14.7}\right)^{0.71} = 9.02 \text{ cu.ft.} \quad \text{(From equation 13, Article 41.)}$$

n = 1.406.

$$\text{Hence } W = 144 \times \frac{53.2 \times 3.62 - 14.7 \times 9.02}{0.406} = 21{,}300 \text{ ft.–lb.}$$

Comparing this with the work of compression, we have:

$$\frac{21{,}300}{47{,}000} = 0.45 = 45 \text{per cent.}$$

That is, theoretically, after cooling down to initial temperature, there still remains in the compressed air energy for doing expansive work to the amount of 45 per cent. of the energy expended in compressing it.

Referring to the diagram in Fig. 17, it will be noted that part of the total work of compression represented by the area MABR is performed by the atmospheric air rushing into the cylinder behind the piston during the compression stroke and not by energy furnished by the compressor. This work is represented by the area MAFR.

In practice, the air, after being compressed, is delivered into the receiver. The work of delivery is jointly performed by the compressor and by the atmospheric air. The compressor' s work is represented by the area FBCD and the work of the atmosphere by the area RFDO. The net work of compression and delivery done by the air compressor alone is represented by the area ABCD. The compressor's share of delivery work is always available for doing useful work in the air engine because in forcing a volume of compressed air from the air-cylinder into the receiver, an equal volume of air is displaced therein, and this displacement process is extended into the pipe line and finally into the air engine, where, in making room for itself, this volume of compressed air drives the piston forward, and thus does useful work.

It may be asked: What becomes of the energy contributed by the atmospheric air toward compression and delivery which is represented by the area MADO in Fig. 17?

This energy is actually stored up in the compressed air when the latter leaves the compressor. It could do useful work if it were practicable to exhaust the air from the engines into a vacuum. But since we must exhaust against atmospheric pressure, the energy is consumed in the process of exhaustion and is therefore not available for useful work. It is not included in the formulas expressing power to be furnished by the compressor because it is furnished gratis by the atmosphere; and it is not included in the formulas expressing the useful work which a volume of compressed air can perform, because it is not available for such work.

The following example shows the effect of heat loss upon the total power stored up in a mass of air by the compressor.

Example.—To compress adiabatically in one stage 100 cu. ft. of free air per minute at sea level to 60 lb. gage and deliver it into the receiver, requires (theoretically) 13.40 h.p. (from column 4 Table V).

If the temperature of the free air was 60° before compression, after compression it will be 375° Fahr. (column 6 Table V) and the volume of the compressed air will be 31.44 cu. ft. (column 5 Table III).

If used immediately after compression, before having lost any heat, it could do work (theoretically) to the amount of 13.40 h.p. by expanding adiabatically down to atmospheric pressure.

But if allowed to cool, before use, to initial temperature under constant volume, the pressure will decrease to a pressure P_3 which we find from the following formula:

$$P_3 = P_2 \frac{T_3}{T_2} = (60 + 14.7)\frac{60 + 461}{375 + 461} = 46.6 \text{ lb. absolute.}$$

A volume of 31.44 cu. ft. of air per minute at 46.6 1b. absolute, if allowed to expand adiabatically down to atmospheric pressure could perform (theoretically) an amount of work found from equation (1) Article 111:

$$\text{Horse–power} = \frac{144nP_2V_2}{33{,}000 \times (n-1)}\left[1-\left(\frac{P_a}{P_2}\right)^{\frac{n-1}{n}}\right]$$

$$= \frac{144 \times 1.406 \times 46.6 \times 31.44}{33{,}000 \times 0.406}\left[1-\left(\frac{14.7}{46.6}\right)^{0.29}\right] = 6.30 \text{ h.p.}$$

which is about 47 per cent. of the power expended in compression and delivery.

When friction and other imperfections are taken into account, this percentage decreases materially.

Adding 15 per cent. to the power of production we get 15.43 h.p.

Subtracting 15 per cent. from the available theoretical energy we get 5.35 h.p. and the comparative value shrinks to 35 per cent. This is further diminished by losses during transmission which are pointed out under Articles 93-94 and 97-105.

c. The answer to the question, why energy still remains in the compressed air after all the heat of compression has been dissipated, is that a certain capacity for work resides in the air which is due to the latter's ability to expand when the proper conditions prevail.

Such conditions could be brought about by confining a volume of atmospheric air in a cylinder under a piston and then create a partial vacuum on the other side of the piston; the atmospheric air in the cylinder would expand and push out the piston, that is, perform work. But creating a vacuum requires extra work, and is therefore not of practical application in air engines.

As a matter of fact, after all the heat generated during compression of a volume of air has been dissipated, the compressed air possesses no more energy than it did before compression, but part of the energy which it did possess has, by mechanical compression, been made available for doing useful work.

To do work, however, the air requires energy in the form of heat and while expanding, it consumes heat that was contained in its mass before compression. As a consequence the temperature of the expanded air falls below that of the surrounding atmosphere. The amount of heat consumed is equivalent to the amount of work performed and equal to the amount of heat that would be generated in compressing this air from the pressure at which it exhausts from the air engine to the pressure at which it enters the same.

The consumption of heat from the mass of the expanding air is manifested by the cold created in and around the cylinders of an engine using air expansively. Theoretically this is exactly the reverse of the generation of heat in the air cylinders of a compressor.

117a. Determination of the Value of "n," used in adiabatic compression and expansion formulas:

From equation (6), Article 117, we have:

Work of adiabatic compression of 1 lb. of free air:

$$W = K_v(T_2 - T_1)\text{foot–pounds} \qquad \textbf{(1)}$$

in which K_v = specific heat of air at constant volume, expressed in foot-pounds.

T_2 = final absolute temperature of air after being compressed to an absolute pressure P_2.

T_1 = initial absolute temperature of air at an absolute pressure P_1.

In the diagram, Fig. 17, the area MABR represents the mechanical work of compressing a volume V_1, of air from an absolute pressure P_1 to an absolute pressure P_2, the volume of compressed air being V_2.

From equation (1) Article 117:

$$\text{Area MABR} = \frac{P_2V_2 - P_1V_1}{n-1} \tag{2}$$

Let P_1 and P_2 be the absolute pressures in pounds per square foot; then the work performed, corresponding to area MABR:

$$W = \frac{P_2V_2 - P_1V_1}{n-1} \text{ foot–pounds} \tag{3}$$

Let, furthermore, V_1 and V_2 represent volumes occupied by 1 lb. of air when under an absolute pressure of P_1 or P_2 respectively; then from equation (5) Article 20:

$$P_1V_1 = RT_1$$

and

$$P_2V_2 = RT_2$$

Substituting these values in equation (3) we have:

$$W = \frac{RT_2 - RT_1}{n-1} = \frac{R(T_2 - T_1)}{n-1} \tag{4}$$

From equation (7) Article 20 we have:

$$R = K_p - K_v$$

Substituting in equation (4) we get:

$$W = \frac{(K_p - K_v)(T_2 - T_1)}{n-1} \tag{5}$$

This work is equal to the work expressed by equation (1), therefore:

$$K_v(T_2 - T_1) = \frac{(K_p - K_v)(T_2 - T_1)}{n-1}$$

or

$$nK_v - K_v = K_p - K_v$$

whence

$$n = \frac{K_p}{K_v} \tag{6}$$

as first stated under Article 40.

INTERNAL OR INTRINSIC ENERGY OF AIR

118. A capacity for doing useful work by expanding against an external resistance, resides in a mass of air as long as its temperature is above the absolute zero. A pound of atmospheric air at 60° Fahr. at sea level, for instance, may be conceived as the outcome of a pound of air at the temperature of absolute zero to which a sufficient amount of heat has been supplied to raise its temperature by (461 + 60) = 521° Fahr., and its pressure to 14.7 lb. above the vacuum.

According to a law of thermodynamics, quoted in previous articles, the heat energy in this pound of air, corresponding to a temperature of 521° above the absolute zero, may be converted into mechanical energy whenever the conditions permit it. The capacity of air of performing work, due to its temperature above the absolute zero, is called the internal or intrinsic energy of air. It is independent of pressure, that is, a pound of atmospheric air at a temperature of 60° Fahr., has the same intrinsic energy as a pound of air under a pressure of 100 lb. having the same temperature of 60° Fahr. (See Articles 119 and 120.)

When applied to practice, there is a vast difference, however, between the pound of atmospheric air and the pound of air at 100 lb. pressure. In the first case none of the intrinsic energy residing in the air is available for useful work under ordinary conditions, whereas in the second case a portion of the intrinsic energy has by mechanical compression been made available for such work.

This may be better understood by comparison with the more familiar generation of water-power. Water flowing down a river possesses intrinsic energy, that is, a capacity for doing useful work when the proper conditions exist. These conditions are brought about by building a dam across the river which raises the water level and thus produces a head, the height of which, together with the amount of water delivered, determines the amount of useful work the water is capable of performing. By building the dam we have added nothing to the intrinsic energy of the water, we have only made available a portion of that energy for performing useful work.

In an analogous manner, by compressing air isothermally, we add nothing to its intrinsic energy, we merely make a portion of that energy available for doing useful work. In actual practice, compression is more or less adiabatic, imparting heat energy to the air, which, however, is subsequently lost in transmission. The condition of the air before use is therefore the same as after isothermal compression.

The conception of internal or intrinsic energy indicates that when air expands without doing work, it loses none of its heat, because the intrinsic energy remains unchanged. The truth of this fact was first proved experimentally by Joule and the fact itself is known as Joule's Law.

119. Intrinsic Energy of a Pound of Atmospheric Air at a Temperature of 60° Fahr.—The specific heat of air under constant pressure is 0.2375, therefore the quantity of heat, that is, the number of B.T.U.'s required to raise the temperature of 1 lb. of atmospheric air from absolute zero to 60° Fahr. is:

$$(461 + 60) \times 0.2375 = 123.74 \text{ B.T.U.'s}$$

and the amount of work corresponding to this quantity of heat is 123.74 × 778 = 96,268 ft.-lb. This is the intrinsic energy of 1 lb. of atmospheric air at 60° Fahr., none of which, however, is available for useful work under ordinary circumstances.

120. Intrinsic Energy of a Pound of Air at 100 lb. Gage and at 60° Fahr.—If permitted to expand adiabatically down to atmospheric pressure against an external resistance, this pound of air would perform work and therefore consume an amount of heat equal to the amount that was generated during adiabatic compression. The theoretical temperature of the air after expansion is deduced from formula (11) Article 41:

$$T_1 = T\left(\frac{P_1}{P}\right)^{\frac{n-1}{n}} = (60+461)\left(\frac{14.7}{100+14.7}\right)^{0.29}$$

$$= 286.55 \text{ degrees absolute.}$$

$$= -174.45^\circ \text{ Fahr.}$$

The drop in temperature is therefore (60 + 174.45) = 234.45 degrees and the number of B.T.U.'s consumed during expansion would be 234.45 × 0.2375 = 55.68 B.T.U.'s.

The equivalent of 55.68 B.T.U.'s expressed in foot-pounds is 55.68 × 778 = 43,321 ft.-lb. This is the amount of intrinsic energy residing in the pound of compressed air which is available for doing useful work.

But there still remains energy in the air which might be used if it were possible for the air to expand down to the absolute zero of pressure, in which case the temperature of the air would drop from 286.55 absolute to the absolute zero of temperature. This represents a consumption of heat units equivalent to (286.55 × 0.2375) = 68.056 B.T.U.'s and these 68.056 B.T.U.'s present work equivalent to (68.056 × 778) = 52,947 ft.-lb. This latter energy is not available for useful work under ordinary circumstances.

The total intrinsic energy of the pound of air at 100 lb. gage and 60° Fahr. is (43,321 + 52,947) = 96,268 ft.-lb. which is the same as the total intrinsic energy of the pound of atmospheric air at 60° Fahr.

(Compressed Air, Theodore Simons, 2nd ed., New York: McGraw-Hill, 1921, p. 113-123.)

The Self-Fueling Air Engine Is A Heat Pump, Not A Perpetual Motion Machine

DEPARTMENT OF ENERGY REPORT

How Efficient Is a Heat Pump?

The efficiency of a home heating system is measured by the number of units of heat energy output obtained for each unit of energy input. Of all the conventional heating systems available today, heat pumps alone can return more heat than they consume.

How can heat pumps multiply their energy input? In simplest terms, while conventional systems use energy to create heat, heat pumps use energy to transfer and intensify heat that is already available in the surrounding environment. A heat pump uses energy only to run the fan and the compressor.

Heat pumps are not new; electric heat pumps were originally developed and marketed in the 1930s.

Even very cold air contains heat--"cold" simply means that some, but not all, of the heat has been removed. For example, at 0° F, air contains 89 percent of the heat available at 100° F. Heat is totally absent from the air only at a temperature of absolute zero, or 460° below 0° F. Thus, even on a cold day, a heat pump can extract some heat from the outdoor air and pump it into a building to maintain a comfortable temperature.

(DOE/CS-0088, May 1979)

REFRIGERATION TEXT

However, this is of less interest than the relationship between the refrigeration produced and the power required. In this case this would be

$$\frac{50.8}{11.2} = 4.52$$

Since this is more than 1.00 or 100 percent it cannot be considered an efficiency. It is called the Coefficient of Performance. In this case there is 4.52 times as much refrigeration produced as power consumed. This is not a form of perpetual motion, since the heat is merely transferred from the evaporator to the condensing water. The compressor is acting in the form of a heat pump to move the heat to the condenser.

(Basic Refrigeration, Guy R. King, 1951)

POPULAR MAGAZINE

The Heat Pump Appears To Do The Impossible

As a home heater, the heat pump seems to achieve the impossible: It moves heat uphill, in a thermal sense, from the cold outdoors to the warmer indoors—in the process, seeming to produce more energy than it consumes. The heat pump is assuming major importance as we rely more on electricity for heating, and its use is mushrooming in the West.

How the "impossible" works.--The key to heat pump economics: The device is just picking up and moving already existing sun-generated heat energy present in even very cold winter air. This can be much less expensive than creating heat with electricity. Under ideal conditions, the coefficient of performance—the ratio of heat output to energy use by the heat pump—can be as high as three to one.

(Sunset, November 1977)

DO-IT-YOURSELF ENERGY SAVINGS MANUAL

As we have seen, the net effect of the heat pump is that energy is removed from a cooler region and "pumped" to a warmer one. Energy does not flow spontaneously from lower to higher temperatures, which is the reason for the compressor. The key question, of course, is how much energy is required to run the compressor? This depends on the operating temperatures involved, but usually we require one unit of compressor energy for every three or four units of energy delivered to the living space. This implies that we receive two or three units of energy "free" from the outside air!

Sounds like magic, doesn't it?

Magic or not, these systems do work. Not only do they work, but the cycle can be reversed in the summer to cool the building! Your local General Electric or Westinghouse dealer can provide you with literature on heat pumps which have been available commercially for nearly two decades. A typical unit is shown in Figure 4.54a.

Heat pumps can be combined with a simple solar collection system for some striking results (see Figure 4.54b). The synergistic effects can be explained in terms of the heat pump's coefficient of performance (*COP* for short). The *COP* is defined in the following way:

$$\text{COP} = \frac{\text{Heat to Living Space}}{\text{Energy Input to Compressor}}$$

In other words, the *COP* is the ratio of what you get out to what you put in..

(Other Homes and Garbage, Leckie, Masters, Young, Whitehouse, Sierra Club Books, 1975)

Tesla's Contribution To Solar Pneumatics

Was Tesla The True Inventor Of The Solar Air Engine?

During the last two decades of the 19th century, while the fledgling compressed air locomotive industry struggled to gain a foothold in the face of competition from steam, electricity, and gasoline, Nikola Tesla was quietly working to invent the means whereby the compressed air engine could be made self-fueling, powered by ambient heat, constantly replenished by the sun.

Tesla knew about the second law of thermodynamics, which states that energy goes from a concentrated, usable form, to a dissipated, less usable form. He disagreed, not with the law itself, but with interpretations of the law which claim that it's virtually impossible for a machine to cool a portion of its environment below ambient temperature in order to draw heat-as fuel into itself, to make itself totally self-fueling. In order to prove that an engine could run on nothing but solar-induced ambient heat, Tesla invented his mechanical oscillator, a reciprocating piston engine with no piston rings, lubrication or valves. By eliminating most of the air engine's moving parts, thereby most of its friction losses, Tesla hoped to give his theory its best chance of working in practice. He then invented a compressor similar in concept to his oscillating engine, eliminating all rotary motion from the resulting air engine/compressor assembly. The engine and compressor were only the first two parts of his five-part plan for a self-fueling solar pneumatic engine.

In the spring of 1895, Tesla was working on the third part of the solar power plant, which he doesn't fully describe in the articlebelow, but its function was to produce refrigeration in a very simple and efficient way. Then his laboratory burned down, and he was never able to finish his invention, though he firmly believed that it would work.

In the June, 1900 article excerpted below Tesla revealed for the first time that his real purpose for inventing the oscillating engine--which he also used as an actuator to generate electricity--was to provide the world with a solar power plant that would run on compressed air and ambient heat. In 1986 I coincidentally got on the same theme of entraining ambient heat for a self-fueling pneumatic power plant, not knowing of Tesla's work in this field. I even chose for my design the oscillating engine Tesla had invented for this express purpose.

Two years after Tesla revealed that his oscillator was meant to be part of a solar power plant, Edward A. Rix of San Francisco published an article in a technical journal about using three-stage air engines to pump water. This is the first and last reference I've ever seen to triple expansion air engines being used in the U.S. Rix gives the results of reheating the cold air between stages with the ambient heat in the water that the engine is pumping. This is basically a groundwater-source heat pump supplying an air engine with a good chunk of its fuel supply for free. Edward Rix was one of the pioneers of modern pneumatics, and the compressor company he founded is still around today. Rix built pneumatic locomotives, published textbooks and articles on the use of compressed air, and received many patents on pneumatic power machinery.

Until early in this century, an air engine would use air expansively to push one piston and then exhaust the air. Because of the large drop in temperature accompanying its

expansion, the air had to be reheated before it could be admitted to the engine, to keep the engine from freezing up. The primary fuel for this reheating was coal which was usually burned to heat water at the filling station. The locomotive would fill up with hot water when it stopped to fill up with air.

In 1904, J. F. Gairns published an article describing the virtues of the Vauclain compound locomotive built for the Philadelphia and Reading Coal and Iron Co. This system, and the H.K. Porter Co.'s system that C. B. Hodges wrote about in 1905, used ribbed cylinders to absorb as much ambient heat as possible to reheat the air.

In 1904, four years after Tesla published his revelation about ambient heat as a fuel source, the same Charles Bowen Hodges of Pittsburgh invented the "atmospheric interheater", which I call the ambient heater. This simple heat exchanger is placed between the stages in a two-stage air engine. The air exhausted from the first-stage cylinder into the interheater is extremely cold and absorbs ambient heat in the interheater before being used again to push the second-stage piston. Thus was eliminated the need to burn coal for the reheating of compressed air in engines.

The compressed air locomotive industry jumped on this idea and adopted it across-the-board beginning in 1907 when Hodges got his patent. From then on, writers on compressed air locomotives focused on the advantages of ambient heat above all other means for reheating compressed air, and the substantial gain in fuel economy resulting from doing so. Hodges got six or seven more patents between 1908 and 1912 for means of using the interheater in compound compressed air locomotives, all of which he assigned to the H. K. Porter locomotive company. From then on, the H.K. Porter Co. seemed to be almost monopolizing a thriving market for compound compressed air locomotives, which were mainly used in mining. The ambient heat resulted in a 30% reduction of fuel consumption by the air engine. This is analogous to modifying a gasoline engine that normally gets 30 mpg, in such a way that it gets about 40 m.p.g.

By 1910, the compound pneumatic locomotive was being used in Britain. Two years later the Europeans took the pneumatic/ambient heat engine two steps further than the Americans would ever take it, by building triple expansion air engines for their mine locomotives. These engines absorbed ambient heat before all three stages, using three ambient heaters to the Americans' one, and consumed 55% less compressed air than they would have without the ambient heat. This is analogous to a gasoline engine that normally gets 30 m.p.g., modified to get almost 50 m.p.g. Triple expansion pneumatic locomotives were used in Britain, France, Germany, Spain, Austria-Hungary, and Belgium. While hundreds of H. K. Porter two-stage locomotives were hauling coal in the U.S., there were hundreds of A. Borsig Co. three-stage locomotives hauling coal in Germany alone.

In July of 1914, the war with Germany began.

In August of 1914 the editor of the Compressed Air Magazine published a disclaimer for his magazine's June article on the triple-expansion pneumatic locomotives being used in Europe. He offered no technical arguments, but in a sarcastic, pro-American vein thrashed out at the idea that triple expansion engines could possibly be as efficient as everybody else was saying they were. Citing no technical evidence whatsoever, but only raving in a Jingoistic fashion, the editor failed to impress anybody and the use of compound pneumatic locomotives continued throughout the 1920s in the U.S. and Europe. Detailed studies on the air consumption of triple expansion pneumatic

locomotives used in France were published in the early 1920s. Successive editions of Robert Peele's widely-used compressed air and mining textbooks continued to emphasize the importance of ambient heat.

I assume that it was the Depression and the Second World War that brought the thriving market for pneumatic/ambient heat engines to a halt in the 1930s.

Whether Nikola Tesla was actually the original source of inspiration for the solar pneumatic engine isn't important, but one more bit of circumstantial evidence should be included here. Sometime after 1910, Tesla formed the Tesla Propulsion Co. in Albany, New York, to develop his steam- or compressed air-powered bladeless turbine for ships and the coal mining industry. In this venture, Tesla's partners were Joseph Hoadley and Walter H. Knight, inventors of the highly successful Hoadley- Knight pneumatic locomotives used for street transit. Hoadley-Knight engines were compound, but still used hot water from filling stations to reheat the air, instead of ambient heaters.

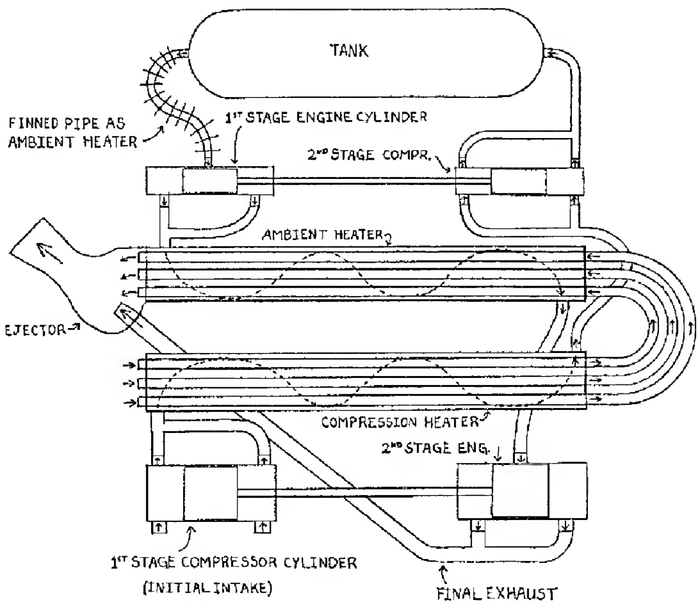
I'd appreciate hearing from anyone who knows of a more complete source of information on Tesla's five-part plan for fueling a solar pneumatic power plant with ambient heat.

"I expect to live to be able to set a machine in the middle of this room and move it by no other agency than the energy of the medium in motion around us." --Nikola Tesla, New York Times, September 30, 1894. (At the time he made the above statement Tesla was, in his words, "pushing vigorously" toward the completion of the linear air engine/compressor that made up the first two parts of his five-part solar pneumatic power plant. His term for ambient heat was "the energy in the ambient medium," almost exactly the same term he used to refer to the fuel source for the self-acting machine he named in the above quote. In 1894 he was keeping it a secret what his ambient energy source was, not revealing till 1900 that it was heat stored in the atmosphere by solar radiation. The above quote has often been assumed to be in reference to some sort of electromagnetic free energy device, but I suspect that this famous quote is actually referring directly to Tesla's then-current experiments on running engines on compressed air and ambient heat.)

A Simple Compound Air Compression Unit Utilizing Ambient Heat
Description of Cycle

Tank starts full from outside source, 250 psi.
Finned pipe absorbs ambient heat to recover energy lost by reduction to 250 p.s.i.
250 psi air enters first stage engine cylinder at ambient temperature, 60° F.
Air expands in cylinder, pushing piston.
Piston pushes second stage compression piston on common shaft.
Partially compressed air already in second stage compression cylinder is compressed further, pumped into tank.
Meanwhile, expanding air in engine cylinder reaches about -75°F. and exhausts into ambient heater at 50 psi.
_75° engine air circulates among heat exchange tubes in ambient heater.
Ambient air at 60° is being drawn by engine's exhaust through heat exchange tubes of first the compression heater and then the ambient heater.

Engine air is warmed to about 45°, thus expanded 31%, by heat that was already in the ambient air, and is simultaneously heated by compression heat just added to ambient air, to well over 60°; compression heat prevents formation of frost in heat exchange tubes of ambient heater,



Solar Air Engine
Two-stage Linear Compression Unit
Scott Robertson, June 6, 1987

Heat exchange tubes in compression heater are surrounded by hot air just compressed by first stage compression cylinder.

Ambient air in compression heater tubes is heated by heat from first stage compression.

Hot compressed air surrounding heat exchange tubes in compression heater is cooled by ambient air, down to ambient temperature, 60°.

Cooled compressed air leaves compression heater and fills second stage compression cylinder on intake stroke.

Hot compressed air leaves ambient heater at 50 psi and enters second stage engine cylinder.

Hot 50 psi air expands and pushes piston.

Piston pushes first stage compression piston on common shaft, compressing ambient air already in compression cylinder.

50 psi air in second stage engine cylinder expands to 5 psi and exhausts to atmosphere through ejector.

Engine exhaust draws ambient air through heat exchange tubes of compression heater then ambient heater by ejector's jet pump action.

On return stroke, first stage compression piston drawn in ambient air.

Engine and compressor based on Tesla concept have no piston rings & no valves except check valves.

Except for check valve parts, entire unit has only two moving parts: the two pairs of pistons on common shafts.

The only friction besides air friction is at the four piston seals and four shaft seals.

The two piston/shaft assemblies don't have to be in exact synch with each other since they aren't linked by any moving parts.

The Problem Of Increasing Human Energy With Special Reference To The Harnessing Of The Sun's Energy

By Nikola Tesla
Century Illustrated Magazine, June 1900

ENERGY FROM THE MEDIUM—THE WINDMILL AND THE SOLAR ENGINE--MOTIVE POWER FROM TERRESTRIAL HEAT—ELECTRICITY FROM NATURAL SOURCES.

But, whatever our resources of primary energy may be in the future, we must, to be rational, obtain it without consumption of any material. Long ago I came to this conclusion, and to arrive at this result only two ways, as before indicated, appeared possible—either to turn to use the energy of the sun stored in the ambient medium, or to transmit, through the medium, the sun's energy to distant places from some locality where it was obtainable without consumption of material. At that time I at once rejected the latter method as entirely impracticable, and turned to examine the possibilities of the former.

It is difficult to believe, but it is, nevertheless, a fact, that since time immemorial man has had at his disposal a fairly good machine which has enabled him to utilize the energy of the ambient medium. This machine is the windmill. Contrary to popular belief, the power obtainable from wind is very considerable. Many a deluded inventor has spent years of his life in endeavoring to "harness the tides," and some have even proposed to compress air by tide- or wave-power for supplying energy, never understanding the signs of the old windmill on the hill, as it sorrowfully waved its arms about and bade them stop. The fact is that a wave- or tide-motor would have, as a rule, but a small chance of competing commercially with the windmill, which is by far the better machine, allowing a much greater amount of energy to be obtained in a simpler way. Wind-power has been, in old times, of inestimable value to man, if for nothing else but for enabling him to cross the seas, and it is even now a very important factor in travel and transportation. But there are great limitations in this ideally simple method of utilizing the sun's energy. The machines are large for a given output, and the power is intermittent, thus necessitating the storage of energy and increasing the cost of the plant.

A far better way, however, to obtain power would be to avail ourselves of the sun's rays, which beat the earth incessantly and supply energy at a maximum rate of over four million horse-power per square mile. Although the average energy received per square mile in any locality during the year is only a small fraction of that amount, yet an inexhaustible source of power would be opened up by the discovery of some efficient method of utilizing the energy of the rays. The only rational way known to me at the time when I began the study of this subject was to employ some kind of heat- or thermodynamic engine, driven by a volatile fluid evaporated in a boiler by the heat of the rays. But closer investigation of this method, and calculation, showed that, notwithstanding the apparently vast amount of energy received from the sun's rays, only a

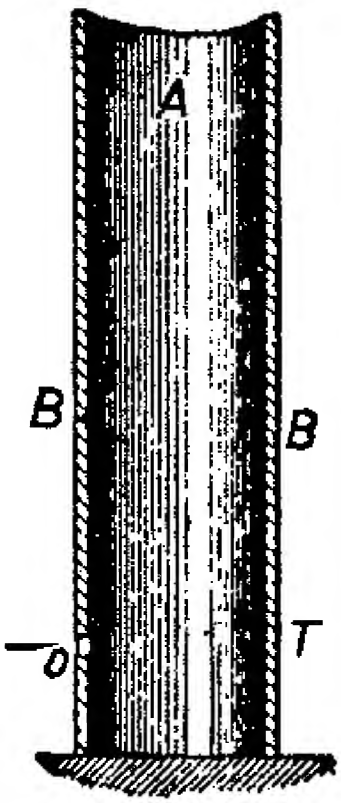


Diagram *b*. OBTAINING ENERGY FROM THE AMBIENT MEDIUM. *A*, medium with little energy; *B*, *B*, ambient medium with much energy; *O*, path of the energy.

small fraction of that energy could be actually utilized in this manner. Furthermore, the energy supplied through the sun's radiation is periodical, and the same limitations as in the use of the windmill I found to exist here also. After a long study of this mode of obtaining motive power from the sun, taking into account the necessarily large bulk of the boiler, the low efficiency of the heat-engine, the additional cost of storing the energy, and other drawbacks, I came to the conclusion that the "solar engine," a few instances excepted, could not be industrially exploited with success.

A DEPARTURE FROM KNOWN METHODS--POSSIBILITY OF A "SELF-ACTING" ENGINE OR MACHINE, INANIMATE, YET CAPABLE, LIKE A LIVING BEING, OF DERIVING ENERGY FROM THE MEDIUM—THE IDEAL WAY OF OBTAINING MOTIVE POWER.

When I began the investigation of the subject under consideration, and when the preceding or similar ideas presented themselves to me for the first time, though I was then unacquainted with a number of the facts mentioned, a survey of the various ways of utilizing the energy of the medium convinced me, nevertheless, that to arrive at a thoroughly satisfactory practical solution a radical departure from the methods then known had to be made. The windmill, the solar engine, the engine driven by terrestrial heat, had their limitations in the amount of power obtainable. Some new way had to be discovered which would enable us to get more energy. There was enough heat-energy in the medium, but only a small part of it was available for the operation of an engine in the ways then known. Besides, the energy was obtainable only at a very slow rate. Clearly, then, the problem was to discover some new method which would make it possible both to utilize more of the heat-energy of the medium and also to draw it away from the same at a more rapid rate.

I was vainly endeavoring to form an idea of how this might be accomplished, when I read some statements from Carnot and Lord Kelvin (then Sir William Thomson) which meant virtually that it is impossible for an inanimate mechanism or self-acting machine to cool a portion of the medium below the temperature of the surrounding, and operate by the heat abstracted. These statements interested me intensely. Evidently a living being could do this very thing, and since the experiences of my early life which I have related had convinced me that a living being is only an automaton, or, otherwise stated, a "self-acting engine," I came to the conclusion that it was possible to construct a machine which would do the same. As the first step toward this realization I conceived the following mechanism. Imagine a thermopile consisting of a number of bars of metal extending from the earth to the outer space beyond the atmosphere. The heat from below, conducted

upward along these metal bars, would cool the earth or the sea or the air, according to the location of the lower parts of the bars, and the result, as is well known, would be an electric current circulating in these bars. The two terminals of the thermopile could now be joined through an electric motor, and, theoretically, this motor would run on and on, until the media below would be cooled down to the temperature of the outer space. This would be an inanimate engine which, to all evidence, would be cooling a portion of the medium below the temperature of the surrounding, and operating by the heat abstracted.

But was it not possible to realize a similar condition without necessarily going to a height? Conceive, for the sake of illustration, an inclosure *T*, as illustrated in diagram *b*, such that energy could not be transferred across it except through a channel or path *O*, and that, by some means or other, in this inclosure a medium were maintained which would have little energy, and that on the outer side of the same there would be the ordinary ambient medium with much energy. Under these assumptions the energy would flow through the path *O*, as indicated by the arrow, and might then be converted on its passage into some other form of energy. The question was, Could such a condition be attained? Could we produce artificially such a "sink" for the energy of the ambient medium to flow in? Suppose that an extremely low temperature could be maintained by some process in a given space; the surrounding medium would then be compelled to give off heat, which could be converted into mechanical or other form of energy, and utilized. By realizing such a plan, we should be enabled to get at any point of the globe a continuous supply of energy, day and night. More than this, reasoning in the abstract, it would seem possible to cause a quick circulation of the medium, and thus draw the energy at a very rapid rate.

Here, then, was an idea which, if realizable, afforded a happy solution of the problem of getting energy from the medium. But was it realizable? I convinced myself that it was so in a number of ways, of which one is the following. As regards heat, we are at a high level, which may be represented by the surface of a mountain lake considerably above the sea, the level of which may mark the absolute zero of temperature existing in the interstellar space. Heat, like water, flows from high to low level, and, consequently, just as we can let the water of the lake run down to the sea, so we are able to let heat from the earth's surface travel up into the cold region above. Heat, like water, can perform work in flowing down, and if we had any doubt as to whether we could derive energy from the medium by means of a thermopile, as before described, it would be dispelled by this analogue. But can we produce cold in a given portion of the space and cause the heat to flow in continually? To create such a "sink," or "cold hole," as we might say, in the medium, would be equivalent to producing in the lake a space either empty or filled with something much lighter than water. This we could do by placing in the lake a tank, and pumping all the water out of the latter. We know, then, that the water, if allowed to flow back into the tank, would, theoretically, be able to perform exactly the same amount of work which was used in pumping it out, but not a bit more. Consequently nothing could be gained in this double operation of first raising the water and then letting it fall down. This would mean that it is impossible to create such a sink in the medium. But let us reflect a moment. Heat, though following certain general laws of mechanics, like a fluid, is not such; it is energy which may be converted into other forms of energy as it passes from a high to a low level. To make our mechanical analogy complete and true, we must,

therefore, assume that the water, in its passage into the tank, is converted into something else, which may be taken out of it without using any, or by using very little, power. For example, if heat be represented in this analogue by the water of the lake, the oxygen and hydrogen composing the water may illustrate other forms of energy into which the heat is transformed in passing from hot to cold. If the process of heat-transformation were absolutely perfect, no heat at all would arrive at the low level, since all of it would be converted into other forms of energy. Corresponding to this ideal case, all the water flowing into the tank would be decomposed into oxygen and hydrogen before reaching the bottom, and the result would be that water would continually flow in, and yet the tank would remain entirely empty, the gases formed escaping. We would thus produce, by expending initially a certain amount of work to create a sink for the heat or, respectively, the water to flow in, a condition enabling us to get any amount of energy without further effort. This would be an ideal way of obtaining motive power. We do not know of any such absolutely perfect process of heat-conversion, and consequently some heat will generally reach the low level, which means to say, in our mechanical analogue, that some water will arrive at the bottom of the tank, and a gradual and slow filling of the latter will take place, necessitating continuous pumping out. But evidently there will be less to pump out than flows in, or, in other words, less energy will be needed to maintain the initial condition than is developed by the fall, and this is to say that some energy will be gained from the medium. What is not converted in flowing down can just be raised up with its own energy, and what is converted is clear gain. Thus the virtue of the principle I have discovered resides wholly in the conversion of the energy on the downward flow.

FIRST EFFORTS TO PRODUCE E THE SELF-ACTING ENGINE—THE MECHANICAL OSCILLATOR--WORK OF DEWAR AND LINDE— LIQUID AIR.

Having recognized this truth, I began to devise means for carrying out my idea, and, after long thought, I finally conceived a combination of apparatus which should make possible the obtaining of power from the medium by a process of continuous cooling of atmospheric air. This apparatus, by continually transforming heat into mechanical work, tended to become colder and colder, and if it only were practicable to reach a very low temperature in this manner, then a sink for the heat could be produced, and energy could be derived from the medium. This seemed to be contrary to the statements of Carnot and Lord Kelvin before referred to, but I concluded from the theory of the process that such a result could be attained. This conclusion I reached, I think, in the latter part of 1883, when I was in Paris, and it was at a time when my mind was being more and more dominated by an invention which I had evolved during the preceding year, and which has since become known under the name of the "rotating magnetic field." During the few years which followed I elaborated further the plan I had imagined, and studied the working conditions, but made little headway. The commercial introduction in this country of the invention before referred to required most of my energy until 1889, when I again took up the idea of the self-acting machine. A closer investigation of the principles involved, and calculation now showed that the result I aimed at could not be reached in a practical manner by ordinary machinery, as I had in the beginning expected. This led me, as a next step, to the study of a type of engine generally designated as "turbine," which at first seemed to offer

better chances for a realization of the idea. Soon I found, however, that the turbine, too, was unsuitable. But my conclusions showed that if an engine of a peculiar kind could be brought to a high degree of perfection, the plan I had conceived was realizable, and I resolved to proceed with the development of such an engine, the primary object of which was to secure the greatest economy of transformation of heat into mechanical energy. A characteristic feature of the engine was that the work-performing piston was not connected with anything else, but was perfectly free to vibrate at an enormous rate. The mechanical difficulties encountered in the construction of this engine were greater than I had anticipated, and I made slow progress. This work was continued until early in 1892, when I went to London, where I saw Professor Dewar's admirable experiments with liquefied gases. Others had liquefied gases before, and notably Ozlewski and Pictet had performed creditable early experiments in this line, but there was such a vigor about the work of Dewar that even the old appeared new. His experiments showed, though in a way different from that I had imagined, that it was possible to reach a very low temperature by transforming heat into mechanical work, and I returned, deeply impressed with what I had seen, and more than ever convinced that my plan was practicable. The work temporarily interrupted was taken up anew, and soon I had in a fair state of perfection the engine which I have named "the mechanical oscillator." In this machine I succeeded in doing away with all packings, valves, and lubrication, and in producing so rapid a vibration of the piston that shafts of tough steel, fastened to the same and vibrated longitudinally, were torn asunder. By combining this engine with a dynamo of special design I produced a highly efficient electrical generator, invaluable in measurements and determinations of physical quantities on account of the unvarying rate of oscillation obtainable by its means. I exhibited several types of this machine, named "mechanical and electrical oscillator," before the Electrical Congress at the World's Fair in Chicago during the summer of 1893, in a lecture which, on account of other pressing work, I was unable to prepare for publication. On that occasion I exposed the principles of the mechanical oscillator, but the original purpose of this machine is explained here for the first time. In the process, as I had primarily conceived it, for the utilization of the energy of the ambient medium, there were five essential elements in combination, and each of these had to be newly designed and perfected, as no such machines existed. The mechanical oscillator was the first element of this combination, and having perfected this, I turned to the next, which was an air-compressor of a design in certain respects resembling that of the mechanical oscillator. Similar difficulties in the construction were again encountered, but the work was pushed vigorously, and at the close of 1894 I had completed these two elements of the combination, and thus produced an apparatus for compressing air, virtually to any desired pressure, incomparably simpler, smaller, and more efficient than the ordinary. I was just beginning work on the third element, which together with the first two would give a refrigerating machine of exceptional efficiency and simplicity, when a misfortune befell me in the burning of my laboratory, which crippled my labors and delayed me. Shortly afterward Dr. Carl Linde announced the liquefaction of air by a self-cooling process, demonstrating that it was practicable to proceed with the cooling until liquefaction of the air took place. This was the only experimental proof which I was still wanting that energy was obtainable from the medium in the manner contemplated by me.

The liquefaction of air by a self-cooling process was not, as popularly believed, an accidental discovery, but a scientific result which could not have been delayed much longer, and which, in all probability, could not have escaped Dewar. This fascinating advance, I believe, is largely due to the powerful work of this great Scotchman. Nevertheless, Linde's is an immortal achievement. The manufacture of liquid air has been carried on for four years in Germany, on a scale much larger than in any other country, and this strange product has been applied for a variety of purposes. Much was expected of it in the beginning, but so far it has been an industrial ignis fatuus. By the use of such machinery as I am perfecting, its cost will probably be greatly lessened, but even then its commercial success will be questionable. When used as a refrigerant it is uneconomical, as its temperature is unnecessarily low. It is as expensive to maintain a body at a very low temperature as it is to keep it very hot; it takes coal to keep air cold. In oxygen manufacture it cannot yet compete with the electrolytic method. For use as an explosive it is unsuitable, because its low temperature again condemns it to a small efficiency, and for motive-power purposes its cost is still by far too high. It is of interest to note, however, that in driving an engine by liquid air a certain amount of energy may be gained from the engine, or, stated otherwise, from the ambient medium which keeps the engine warm, each two hundred pounds of iron casting of the latter contributing energy at the rate of about one effective horse-power during one hour. But this gain of the consumer is offset by an equal loss of the producer.

Much of this task on which I have labored so long remains to be done. A number of mechanical details are still to be perfected and some difficulties of a different nature to be mastered, and I cannot hope to produce a self-acting machine deriving energy from the ambient medium for a long time yet, even if all my expectations should materialize. Many circumstances have occurred which have retarded my work of late, but for several reasons the delay was beneficial.

One of these reasons was that I had ample time to consider what the ultimate possibilities of this development might be. I worked for a long time fully convinced that the practical realization of this method of obtaining energy from the sun would be of incalculable industrial value, but the continued study of the subject revealed the fact that while it will be commercially profitable if my expectations are well founded, it will not be so to an extraordinary degree.

It is probable that we shall soon have a self-acting heat-engine capable of deriving moderate amounts of energy from the ambient medium. There is also a possibility—though a small one—that we may obtain electrical energy direct from the sun. This might be the case if the Maxwellian theory is true, according to which electrical vibrations of all rates should emanate from the sun. I am still investigating this subject. Sir William Crookes has shown in his beautiful invention known as the "radiometer" that rays may produce by impact a mechanical effect, and this may lead to some important evelation as to the utilization of the sun's rays in novel ways.

Compressed Air Is Under-Rated As An Energy Carrier By The Engineering Establishment

Amory Lovins: Keynote Speaker for Sustainable Energy

THE PLOWBOY INTERVIEW

PLOWBOY: Perhaps you could explain what you mean by that...by matching "energy quality" to end-use needs. What does that mean?

LOVINS: Well as you know, energy comes in many different forms, some of which are what a scientist would call "low grade" energy. That isn't a derogatory term...it just means that the kind of energy in question—low-temperature heat, usually—can't do difficult kinds of work. Now, there's an awful lot of low-grade energy around. There's more low-grade energy in the Atlantic Ocean, for instance, than there is high-grade energy in all the oil in the Middle East, but you can't do much with it.

By matching energy quality to end use needs, I simply mean that where you have a job that can be done by low-grade energy, you should use low-grade energy to do that job, and not high-grade energy.

PLOWBOY: Is there much of a need for low-grade energy in this country?

LOVINS: Oh yes. About half of all the energy needed in the U.S. today is required in the form of heat at temperatures below a few hundred degrees Celsius. Altogether something like 58% of our end-use needs are for heat. And only a fraction of that 58% Is high-temperature heat.

PLOWBOY: How do you answer critics who say that energy storage is a major problem with soft technologies?

LOVINS: I think they've got it backwards. Energy storage is a major problem with hard technologies. It's a minor problem with soft technologies. The reason for this is that with soft technologies, you aren't trying to electrify everything or store large amounts of energy. You would instead be trying—where you needed storage—to store energy at the point of end use, in rather small amounts, and often at rather low quality. Now it's very simple to store low-temperature heat...you can do it in water or rocks. There might be more elegant ways to do it, but you don't need them.

Again, let's go through the kinds of energy we're talking about. Low- and high-temperature heat would be stored as heat, at the point of end use. That's easy. Liquid fuels would be stored as liquid fuels. That's easy...we're already doing it. Electricity would be stored as water behind existing dams. We're already doing that too. That's all there is, except maybe for mechanical energy, which you can always store as compressed air.

> *Soft technologies are diverse . . . rely on renewable energy flows . . . are understandable . . . and are matched in scale and energy quality to end-use needs.*

PLOW BOY: Compressed air? That's not very practical, is it?

LOVINS: I think it is. Some European cities--Paris and Vienna, for example—used to offer compressed air as a standard utility. It ran all the motors in those towns until the turn of the century, when electricity took over. Compressed air is actually a very highly developed technology. I recently looked in the Yellow Pages of the phone book in a large American city, under the heading "Compressed Air", and there were something like six pages of listings!

Compressed air is very handy stuff. It's exceedingly simple and reliable. It's spark proof, which—of course--is why it's used so much in mining. And it has good torqueing characteristics...

Anyway, I think compressed air has been much under-rated as an energy carrier.

(Mother Earth News, November/December 1977)

Amory Lovins (Director of Research, the Rocky Mountain Institute, Snowmass, Colorado), a consultant experimental physicist, was educated at Harvard and Oxford. He holds an Oxford MA and five honorary doctorates, has taught at many universities, and has been active in energy policy in more than 15 countries. A Fellow of the American Association for the Advancement of Science and former member of the Department of Energy's senior advisory board, he has published a dozen books and over 100 papers. His energy consultancy to many national, state, and local governments and to private firms has made him, in Newsweek's terms, "one of the Western world's most influential energy thinkers." He and Hunter shared a 1982 Mitchell Prize and a 1983 Right Livelihood Award (often called the "alternative Nobel Prize").

(Rocky Mountain Institute Newsletter)

High-Torqueing Characteristics of Air

Unlike the internal combustion engine, the expansion engine--powered either by steam or compressed air--has maximum torque at starting speed. This makes it perfect for climbing hills and starting under a load, something that cannot be said about the i.c. engine. The i.c. engine is a Rube Goldberg device that has been developed to take advantage of a temporary and profitable abundance of petroleum; it runs at a high temperature, wasting more energy than it uses productively, and becomes completely useless if its temperature increases a few degrees above its normal operating temperature. Its desire to do nothing requires the use of high engine speeds just to get usable torque out of it, making it necessary to install and maintain expensive, heavy, and complicated multi-speed transmissions.

The expansion engine, on the other hand, develops high torque when it's needed most, and was perfected almost a hundred years ago. In 1906, the world speed record of the time was set by a steam-powered race car at 127.66 m.p.h. In 1915, an article in the Transactions of the Society of Automobile Engineers made the following statement:

> The authors cannot close without recording a protest against the use of horsepower as a unit for motor car rating. Whatever may be its value in the classification of motor car engines, it seems utterly inconsistent to apply it to the performance of a vehicle. *It is the pull or push* of the tire on the road that is effective in the propulsion of a car. Witness the utter absurdity of a steam car equipped with a 20-H.P. engine, outpacing and outclimbing gas cars, the engines of which will develop upwards of 80 H.P. on the block. The steam car accomplishes this by greater and more uniform torque (or turning moment) delivered to its rear wheels through the continued and overlapping admission of high cylinder-pressures; therefore it is clearly this torque, or turning effort, that should be recognized, and its direct and easily measurable result, drawbar pull, seems to be the logical, final unit of such measurement.

Bill Truitt of McKees Rocks, Pennsylvania, has built three air cars since 1920. He perfected his designs from 1974-1980. One of his air cars has been up to 136 m.p.h. He had to put a limiter on the accelerator pedal because it was scary to drive. Lee Rogers' air car will reportedly lift the front wheels slightly when starting too fast. His car can go 80 m.p.h. Terry Miller's prototype air car, which is a workbench on wheels, can pull a large pickup truck up a slight incline from a dead stop. Terry's air car weighs 1500 lbs.; the engine puts out about 5 h.p., and runs at a maximum of 50 r.p.m.

Chapter 2: Air Engine Theory

General Theory

Compressed air can be used to deliver motive power to an engine at full pressure or expansively, or somewhere in between--partial expansion. When working at full pressure the air is admitted to the cylinder throughout practically the entire length of stroke, that is, without cutoff, so that nearly a cylinderful of air at gauge pressure is exhausted at each stroke.

The term "expansive" means that the air enters the cylinder during only a part of the stroke, and is then cut off and the stroke completed by the expansion of the air. For operating in this way some equalizing agent, such as the flywheel, is essential, and as a rule a higher initial pressure is employed than when working under full pressure throughout the stroke. It is necessary to distinguish between complete and partial expansion. When the air is used with complete expansion the operation in the cylinder is the reverse of adiabatic compression in a compressor, the final pressure equal to that of the atmosphere. But as air does not undergo condensation, the lowest terminal pressure in the cylinder must still be sufficiently above atmospheric pressure to produce a proper exhaust, and to overcome the friction of the engine at the end of the stroke. Therefore, it is not practical to attempt truly complete expansion.

For economy of air use, air engines should work with partial but nearly complete expansion, the air expanding adiabatically in the latter part of the stroke. The point of cutoff is chosen such that the terminal cylinder pressure exceeds atmospheric pressure only enough to cause a free exhaust. Any non-condensing steam engine can be run on compressed air. In all non-condensing steam engines, even with an early cut-off the proportions are such as to maintain at the end of the period of expansion, a sufficient steam pressure to insure a speedy exhaust of the gaseous and of the condensed steam. This pressure must of course be greater in a fast moving than in a slow engine, with the consequence that part of the energy of the steam is thus sacrificed, not uselessly, but without doing useful work.

But with air, there is no condensation during the expansion, and also the active gas which drives the piston is the same as the medium into which it is discharged, so the exhaust pressure may become a very insignificant quantity. The result of this is two-fold: First, an air engine, unlike a steam engine, can work practically at complete expansion; the compressed air can expand down to nearly atmospheric pressure; and second, this more prolonged expansion will be accompanied by a greater fall of temperature. The genuine air engine is inseparable from a system of reheating. Also, since the complete expansion of air produces a greater variation of load on the piston, an air engine should preferably be compound, rather than single-stage. The Tech Development Co. in Dayton, Ohio, manufactures an air turbine that has the same high-torque-at-startup-speed characteristic as a piston expansion engine. It is 70% efficient at all speeds, using only 17 cfm of cold air per hp produced, compared to about twice that much air used by the average air motor. The reason for the relatively high efficiency is that the turbine is a *compound* air motor; it expands the air fully.

While an ordinary non-condensing steam engine will perform satisfactory duty if operated with air, a lower consumption of it will be obtained by cutting off earlier in the stroke so as to work at complete expansion. This will diminish the mean effective pressure throughout the stroke, and, consequently, the power developed by the engine, at the same time increasing the range of variation of stresses on the engine parts.

This would be acceptable if the load on the engine was regular, but if the load constantly varies or else is intermittent, the air engine at complete expansion must have its valve gear so arranged as to allow a later cutoff and a greater or smaller amount of exhaust pressure, which means that it must be an ordinary steam engine capable of an earlier cutoff than is normally used with steam.

Although, in principle, compressed air is used like steam, both being elastic fluids, there is an essential difference in the results, due to the reduction in temperature when compressed air expands. In expanding behind the piston, a given volume of compressed air at a given pressure will not produce the same amount of power as steam under the same conditions; steam carries excess heat, whereas compressed air carries just enough. The lower mean (average) effective pressure of air is due to the development of cold during its expansion. This is the reverse of compression, and the resulting loss of motive power is analogous to the loss of work in the compressor caused by the generation of heat. Just as the heat of compression produces a higher pressure than that due to just the reduction in volume, when expansion takes place, the air, which is usually at normal atmospheric temperature on entering the cylinder, rapidly gives up its *sensible heat*--the heat we can tell is there with our senses; air that's cold to the senses still contains lots of heat--and the cold reacting upon the expanding air reduces its pressure faster than that which is due to the increase in volume. In the case of steam, the initial temperature is high, and is only reduced a little during expansion from ordinary working pressures down to atmospheric pressure.

The expansion of air produces such low temperatures, that for a long time the expansive use of compressed air was not considered practicable. In Table 1 are given the theoretical final temperatures of the exhaust air, in working with complete expansion, and also at full pressure throughout the stroke, for different ratios of initial to final pressure, together with the theoretical efficiencies. The initial temperature is taken at 68° F.[1]

The table shows that by working at full pressure extremely low temperatures of exhaust are avoided; but using compressed air this way is much less efficient than that of expansion. The temperatures given here are theoretical and are never actually reached in practice. The cold produced is modified by several causes: (1) some heat is transmitted from the surrounding atmosphere through the cylinder walls; (2) the recompression of the *clearance* air--the unswept volume at the end of the stroke, necessary to prevent the piston from banging into the cylinder head, and because of nooks and crannies between cylinder and valve, and other design constraints--at each stroke produces heat in the cylinder, to a degree that increases with the initial pressure and the clearance volume; and (3) the presence of moisture in the air tends to raise the air temperature, since water holds heat longer than air.

[1] *M. Mallard, "Étude Théorétique sur les Machines à Air Comprimé," p. 27; my source for most of the information in this section is Compressed Air Plant, Robert Peele, 5th ed., New York: Wiley, 1930 (ed.).

TABLE 1.--TEMPERATURES OF EXHAUST AIR

Ratio of initial to final pressure	Working with Complete Expansion		Working at Full Pressure	
	Final Temperature, degrees F.	Theoretical efficiency	Final Tempera-ture, degrees F.	Theoretical efficiency
2	-28.2	0.855	-8.4	0.82
3	-76.0	0.806	-34.5	0.72
4	-106.6	0.782	-45.7	0.67
5	-128.2	0.768	-54.4	0.63
6	-144.4	0.758	-59.8	0.60
7	-158.8	0.751	-63.4	0.57
8	-170.8	0.746	-66.1	0.55
9	-180.6	0.742	-68.0	0.53
10	-189.2	0.739	-69.7	0.51

A brief mathematical description follows concerning the three main modes of expansion in compressed air engines: working at full pressure (non-expansive), with partial expansion, or with complete expansion.

1. Working at Full Pressure.—This mode of using compressed air is used in commercial air motors, which are designed for maximum portability and convenience, rather than efficiency. The work in foot-pounds done by such an engine is equal to the effective intake pressure in pounds per square feet, multiplied by the volume of the cylinder in cubic feet. The effective intake pressure is the absolute pressure of the air supplied to the cylinder minus the backpressure. Usually this is roughly the same as the gauge pressure of the intake air, though for greater accuracy the standard value for atmospheric pressure, 14.7 psia, can be corrected for elevations other than sea level. This formula, $W = V_I(P_I - 14.7)$ is simply force times the distance through which the force acts. As explained in the chapter on thermodynamics, pressure × area × stroke is equivalent to pressure × volume, and force × distance. As no work is done by the expansive force of the air, all the initial pressure is still present in the exhaust except for what is lost along the way due to turbulence, sharp bends in piping, etc. The piston moves because of the pressure difference between the working air and the atmospheric backpressure, but more air is entering right behind it, so it has no chance to expand. This type of steady push is necessary in such things as rock drills and small portable tools. Unfortunately it has become an industry standard, and modern textbooks do almost nothing to enlighten us to more efficient ways of using air. Although I stressed above that it is heat, and not pressure, that pushes pistons, in this case it appears that there is no change in temperature, therefore no use of heat. This is an illusion, however; it's still heat doing the work, but the steady supply of air creates a situation where there is no theoretical change of temperature or pressure.

2. Working with Partial Expansion.—The advantages of using compressed air in this way can be obtained from engines possessing flywheels, if the cutoff is not too early in the stroke to avoid excessive reduction of cylinder temperature, or if the air is reheated before entering the cylinder, and between stages in compound engines.

In this case the initial values of pressure, volume, and temperature are P_I, V_I, and T_I respectively. From the point of cutoff the air expands adiabatically down to a terminal pressure of P_x and volume V_x, the final temperature in the cylinder falling to T_x. On exhausting, the pressure, volume and temperature become P, V, and T, the atmospheric conditions; for P we will use 14.7, the value at sea level. The work done, W, is composed of three parts:

W' = work between the point of admission and the point of cutoff = $P_I V_I$;

W'' = work performed by expansion of the volume V_I from the point of cutoff to the end of the stroke $= 778wC_v(T_I - T_x)$;

W''' = negative work due to backpressure $= -14.7V_x$.

Taking the algebraic sum of these three quantities:

$$W = P_I V_I + 778wC_v(T_I - T_x) - 14.7V_x$$

According to the General Gas Law, $V_I = \dfrac{wk_G T_I}{P_I}$

and $V_x = \dfrac{wk_G T_x}{P_x}$

Substituting these values of V_I and V_x, and for k_G and C_v, their numerical values of 53.37 and 0.1689:

$$W = w\left[53.37T_I + 131.4(T_I - T_x) - 53.37T_I\left(\frac{14.7}{P_x}\right)\right]$$

$$= 53.37w\left[T_I + 2.46(T_I - T_x) - T_I\frac{14.7}{P_x}\right]$$

3. Working with Complete Expansion.—When the expansion is adiabatic, the same relations exist between pressures, volumes, and temperatures as in adiabatic compression:

$$\frac{P_I}{P} = \left(\frac{V}{V_I}\right)^{n=1.406} = \left(\frac{T_I}{T}\right)^{\frac{n-1}{n}=0.29}$$

The theoretical work done by complete adiabatic expansion may be expressed by a formula like that employed for compression, but with an inversion of certain of the quantities, thus:

$$W = \frac{n}{n-1}PV\left[1 - \left(\frac{P}{P_I}\right)^{\frac{n-1}{n}}\right],$$

in which W = theoretical foot-pounds of work done by the expansion to atmospheric pressure of 1 lb. (13.1 cu.ft.) of free air. Substituting the values of the constants, and for working at sea-level:

$$W = 3.463 \times 144 \times 14.7 \times 13.1 \times \left[1 - \left(\frac{14.7}{P_I}\right)^{0.29}\right]$$

$$= 96{,}029\left[1 - \left(\frac{14.7}{P_I}\right)^{0.29}\right]$$

For example, if P_I is 40 psig:

$$W = 96{,}029\left[1 - \left(\frac{14.7}{54.7}\right)^{0.29}\right] = 30{,}440\,\text{ft.lb., or } 2323\ \text{ft.lb. per ft.}^3\ \text{of free air.}$$

Actual Work Done.—In the above expressions no account is taken of the friction of moving parts, or losses caused by leakage. In determining the actual work, the general case will be where a cutoff is used. The relations between initial and terminal pressures and temperatures, for different ratios of expansion in a cylinder, are shown in Table II.[2] The points of cutoff, in tenths of the cylinder stroke, are given in the first column.

The quantities in Table II must be further corrected for piston clearance and the lost volume represented by the air ports and passages of the cylinder, because part of the air expands into these clearance spaces. Therefore, the actual effect of the cutoff, in any given case, is found by dividing the sum of the cutoff plus clearance, by the cylinder volume plus clearance. For example, if the stroke is 10, with a cutoff of 4/10, and clearance of 6 per cent, the actual volume of the cylinder, including clearance, will be: $(10 \times 0.06) + 10 = 10.6$. Then the sum of the cutoff plus the clearance is $4 + .6 = 4.6$, and the working cutoff becomes $4.6 \div 10.6 = 0.434$. In this manner Table III has been constructed, for use in connection with Table II. It shows the actual cutoff corresponding to the different nominal points of cutoff, for the percentages of piston clearance named at the top of the columns.

The theoretical terminal cylinder pressure resulting from adiabatic expansion may be expressed by:

$$\frac{P_I}{C^{1.406}} - 14.7,$$

in which $C = \text{ratio of expansion} = \dfrac{1}{\text{point of cutoff}}$ (see column 2, Table II).

For example, for a cutoff of 4/10 stroke and 65 psig, the terminal pressure (above atmospheric pressure) will be:

$$\frac{65 + 14.7}{2.5^{1.406}} - 14.7 = 7.2\ \text{psig.}$$

[2] This table, as well as Table III, is taken in part from those used by G. D. Hiscox, in Compressed Air, its Production, Uses and Application.

The volume corresponding to the nominal cutoff is increased by the clearance, and adds to the mean pressure. Thus, in the above example, assuming the clearance to be 6%, the actual cutoff (Table III) is increased from 0.4 to 0.434, of which the ratio C is $\frac{1}{0.434} = 2.3$. From Table II, column 7, the ratio of

TABLE II.--THEORETICAL RATIOS OF PRESSURES AND TEMPERATURES DUE TO THE EXPANSION OF COMPRESSED AIR IN AN ENGINE CYLINDER

Cutoff	Ratio of expansion = 1 ÷ cutoff	Ratio of mean to total absolute pressure, for entire stroke	Ratio of mean to total absolute pressure, during expansion only	Ratio of initial to final temperatu re	Ratio of initial to final absolute tem- perature, due to expansion only	Rato of inital to final absolute pressure for ratio of expansion
.10	10.00	.249	.166	.391	.513	.039
.15	6.67	.348	.233	.460	.578	.069
.20	5.00	.436	.295	.518	.627	.104
.25	4.00	.515	.353	.568	.669	.142
.30	3.33	.585	.408	.612	.705	.184
.35	2.86	.647	.460	.652	.737	.228
.40	2.50	.706	.510	.688	.767	.275
.45	2.22	.757	.558	.722	.794	.325
.50	2.00	.802	.604	.754	.818	.378
.55	1.81	.842	.649	.784	.841	.433
.60	1.67	.877	.692	.812	.862	.487
.65	1.54	.907	.734	.839	.882	.545
.70	1.43	.932	.774	.865	.902	.605
.75	1.33	.954	.814	.889	.920	.667

initial to terminal pressure, corresponding to the actual cutoff of 0.434, is (by interpolation) 0.31; whence: $(79.7 \times 0.31) - 14.7 = 10 \text{lb.ter} \min \text{al}$ pressure.

Cylinder Volume Required for a Given Power.—The work per stroke is found by dividing the foot-pounds of work to be done per minute by twice the number of revolutions of the engine, assuming the cylinders are double-acting. (Expansion engines don't run over 1000 rpm, and less is better, since the longer the air is in the engine, the more time it has to absorb ambient heat. Terry Miller's engine ran at a maximum of 50 rpm, and if the engine is crude or experimental or less than professionally designed or built, then slow engine speeds are preferable.)The work per stroke is substituted, with the initial and final pressures, in the formula for working with full pressure, partial or complete expansion, as the case may be, which is then solved for the initial volume, V_I', of compressed air used per stroke. To the theoretical cylinder volume thus found, the allowance for piston clearance is added, according to the type of engine. The proper proportion between stroke and diameter of cylinder is finally determined.

The volumes of free air per minute, required for an air engine, per indicated horsepower and for different ratios of cutoff, are shown in Table IV, by F. C. Weber.[3] The figures given in this table do not include the volume corresponding to piston clearance, which may be found as already shown.

Nominal cutoff	Percentage of Clearance						
	.03	.04	.05	.06	.07	.08	.10
.10	.126	.135	.143	.151	.159	.167	.182
.15	.175	.184	.191	.198	.206	.213	.227
.20	.223	.231	.238	.245	.252	.259	.273
.25	.272	.279	.286	.293	.299	.305	.318
.30	.320	.327	.333	.340	.346	.352	.364
.35	.368	.376	.380	.387	.392	.398	.409
.40	.417	.423	.429	.434	.439	.444	.455
.45	.465	.471	.477	.481	.486	.490	.500
.50	.514	.519	.524	.528	.533	.537	.546
.55	.564	.568	.571	.576	.580	.585	.591
.60	.612	.615	.619	.623	.626	.630	.637
.65	.660	.664	.667	.670	.673	.676	.682
.70	.709	.711	.714	.717	.720	.722	.727
.75	.758	.760	.762	.764	.766	.768	.772

TABLE III.-ACTUAL CUTOFF DUE TO CLEARANCE, FOR THE NOMINAL CUTOFFS IN COLUMN 1

In this table the air is supposed to be used without reheating, and at an initial temperature of 60° F. Reheating will reduce the volume of air proportionally to the ratio $\frac{T_2}{T_3}$, where T_2 = 459° + 60° = 519° F., or absolute temperature; and T_3 = 459° plus the temperature of the reheated air on entering the motor cylinder. Thus, if the air is reheated to 200° F., the above ratio becomes 519°/659° = 0.787, by which decimal the volume of air as found in the table must be multiplied.

While everything in this book is of importance, and hopefully you will take the time to absorb the material in more than a superficial way, those of you who can't take this much time will be encouraged to know that the tables in this chapter should be enough to keep you within the bounds of reality when you consider what can and can't be done with compressed air, even if you bypass all the mathematical formulas from which they are built.

For the practical formula used to determine the actual dimensions of an air engine, and the power required for a certain task, see the chapter on "Vehicle Power Requirements."

The first thing you'll notice about Table IV is that the modern "air motors" sold

[3] Compressed Air, Oct., 1896, p. 117.

Point of cutoff	Gauge Pressures, psig									
	30	40	50	60	70	80	90	100	110	125
1	23.3	21.3	20.2	19.4	18.8	18.42	18.10	17.8	17.62	17.40
3/4	18.7	17.1	16.1	15.47	15.0	14.6	14.35	14.15	13.98	13.78
2/3	17.85	16.2	15.2	14.5	14.2	13.75	13.47	13.28	13.08	12.90
1/2	16.4	14.5	13.5	12.8	12.3	11.93	11.7	11.48	11.30	11.10
1/3	17.5	15.2	12.9	11.85	11.26	10.8	10.5	10.21	10.02	9.78
1/4	20.6	15.6	13.4	13.3	11.40	10.72	10.31	10.0	9.75	9.42

TABLE IV.--CUBIC FEET OF FREE AIR PER MINUTE USED BY AIR ENGINE, PER I.H.P.

commercially are totally off the chart as far as their inefficiency. It's no wonder that your friendly neighborhood engineer is calling the men in white coats to come and get you, at this very moment. How could anyone have told him wrong? The answer is, they didn't; they just sold him short.

Specific Engine Types and Compound Expansion

Tables are given here (Figs. 1-5) of the consumption of air per minute, reduced to atmospheric pressure, in three classes of expansion engines* more commonly used:

The Slide Valve Engine,

The Automatic Cut-off Engine, Single and Compound,

The Corliss Engine, Single and Compound.

Air, in most cases, expands in a motor somewhat adiabatically; i.e., its expansion is accompanied by a considerable fall of temperature. Fig. 7 gives the temperature of the exhaust after working expansively in these types of engines. This temperature is found to range from +7.5° F.in the slide valve engine to -143° F. in the Compound Corliss, cutting off at 1/3 of stroke (33% cutoff), the air being admitted to the engine at 60° F. While the former temperature might not prove troublesome with dry air, on account of the strong exhaust blast of an engine with a late cut-off, the latter might be troublesome, unless the seals and lubricant used in the cylinder are chosen for such low temperatures; and the exhaust ports would become clogged with ice, especially in a humid environment.

If the cutoff to be used will reduce the temperature of the air to below 32° F., it will be necessary to heat it to a certain extent before it enters the cylinder, or during the process of its expansion within the cylinder, or both. We know already that this operation has also the effect of increasing the volume of the air at constant pressure. Two curves (Fig. 6) are here presented** showing the increase of volume of 1 ft^2 of air, at 32 ° F. and at 60 ° F., when heated to various temperatures up to 600° F.

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* For more details on the valve arrangements that distinguish one type of engine from another, see the chapter on engine valves.

** Most of the information in this section is taken from A Practical Treatise on Compressed Air, Edward A. Rix and A. E. Chodzko, San Francisco: Fulton Engineering and Shipbuilding, 1896.

Size of Engine (inches)	R.P.M.	Piston Velocity (ft./min.)	CFM Free Air consumed at Throttle Pressure (psig) and Corresponding Brake Horsepower					
			60 psi	bhp	70 psi	bhp	80 psi	bhp
6 × 8	250	333	232.7	8.6	264	10	295	11.5
7 × 10	240	400	380	14	431	16.4	482	18.8
8 × 10	240	400	496.3	18.3	562.8	21.5	629.2	24.5
9 × 12	200	400	628.4	23.2	712.5	27.2	796.6	31
10 × 12	200	400	775.7	28.7	879.6	33.6	983.4	38.4
10 × 14	200	467	904.8	335	1025.9	39.2	1147	44.8
11 × 14	200	467	1094.7	40.6	1241.3	47.5	1387.8	54.1
12 × 16	180	480	1341.1	49.7	1520.6	58	1699.2	66.5

Fig. 1: Free Air at 14.7 psia consumed per minute in

SLIDE VALVE ENGINES

- Clearance is assumed to be 7% of cylinder capacity.
- Cutoff at 5/8 of stroke.
- Brake horsepower is taken as .85 of indicated horsepower.
- Initial pressure in cylinder is taken as .95 of pressure at throttle.

Size of Engine (inches)	R.P.M.	Piston Velocity (ft./min.)	CFM Cold Air consumed at Throttle Pressure (psig) and Corresponding Brake Horsepower							
			60 psi	bhp	70 psi	bhp	80 psi	bhp	90 psi	bhp
7 × 9	300	450	182.9	12.8	207.4	15.3	231.8	17.8	255.6	20.4
	360	540	219.5	15.3	248.8	18.4	278.2	21.4	306.7	24.4
8 × 9	300	450	239.8	16.7	271.9	20	304	23.3	335.1	26.6
	360	540	288	20	326.6	24	365.1	28	402.6	32
9 × 9	300	450	302.3	21.1	342.7	25.4	383.2	29.5	422.5	33.7
	360	540	362.7	25.3	411.3	30.4	459.8	35.4	506.9	40.4
9½ × 10½	270	472.5	353	23.9	400.3	28.7	447.6	33.4	493.5	38.1
	330	577.5	431.3	28.7	489	34.4	546.8	40	602.8	45.7
10½× 10½	270	472.5	482.3	29.2	490.2	35.1	548	40.8	604.2	46.6
	330	577.5	527.8	35	598.5	42.1	669.1	49	737.7	56
11 × 12	240	480	482.6	32.5	547.2	39.1	611.8	45.5	674.5	52
	300	600	603.5	40.6	684.3	48.9	765.1	56.8	843.5	64.9
12½ × 12	240	480	623.3	42	706.8	50.5	790.2	58.7	871.1	67.1
	300	600	718.8	52.5	883	63.1	987.3	73.4	1033.4	83.9

Fig. 2: Cold Air at 14.7 psia consumed per minute in

SINGLE-CYLINDER AUTOMATIC CUTOFF ENGINES

- Clearance is assumed to be 5% of cylinder capacity.
- Cutoff at 1/4 of stroke.
- Brake horsepower is taken as .85 of indicated horsepower.
- Initial pressure in cylinder is taken as .95 of pressure at throttle.

Size of Engine (in.)	R.P.M.	Piston Speed (ft./min.)	CFM Free Air consumed at Throttle Pressure (psig) and Corresponding Brake Horsepower											
			80 psi				90 psi				100 psi			
			1/4 cutoff	bhp	1/5 cutoff	bhp	1/4 cutoff	bhp	1/5 cutoff	bhp	1/4 cutoff	bhp	1/5 cutoff	bhp
10 × 24	90	360	353.6	27	290.4	22	389.8	34	320.2	26	428.2	36	351.8	30
10 × 30	90	450	441.8	33	363.2	28	487	39	400.4	33	535.1	44	440	37
12 × 30	90	450	637.6	48	523.6	40	702.9	56	577.2	47	772.2	64	634.1	54
12 × 36	90	540	764.4	58	627.9	48	842.8	67	692.2	56	925.9	77	760.5	65
13 × 30	90	450	746.4	56	613	47	822.9	66	675.9	55	904	75	742.6	63
13 × 36	90	540	895.8	68	736	56	987.6	79	811.5	66	1085	90	891.5	76
14 × 36	90	540	1042	79	855.9	66	1148.8	92	943.6	77	1262	106	1036.6	88
14 × 42	85	595	1148.3	87	942.8	73	1265.9	101	1039.4	85	1390.7	117	1141.9	97

Fig. 4: Free Air at 14.7 psia consumed per minute in

SINGLE-CYLINDER CORLISS ENGINES

- Clearance is assumed to be 3% of cylinder capacity.
- Brake horsepower is taken as .85 of indicated horsepower.
- Initial pressure in cylinder is taken as .95 of pressure at throttle.

Size of Engine (inches)	R.P.M.	Piston Velocity (ft./min.)	CFM Free Air Consumed at Effective Throttle Pressure = 100 psig	Brake Horsepower
10 & 15 × 30	85	425	651	53
12 & 18 × 36	83	498	1099	94
14 & 22 × 36	83	498	1496	126
14 & 22 × 42	75	525	1577	133

Fig. 5: Free Air at 14.7 psia consumed per minute in

COMPOUND CORLISS ENGINES

- Clearance is assumed to be 3% of high pressure cylinder capacity.
- Cutoff at 1/3 of stroke in high pressure cylinder
- Brake horsepower is taken as .85 of indicated horsepower.
- Initial pressure in high pressure cylinder is taken as .95 of pressure at throttle.

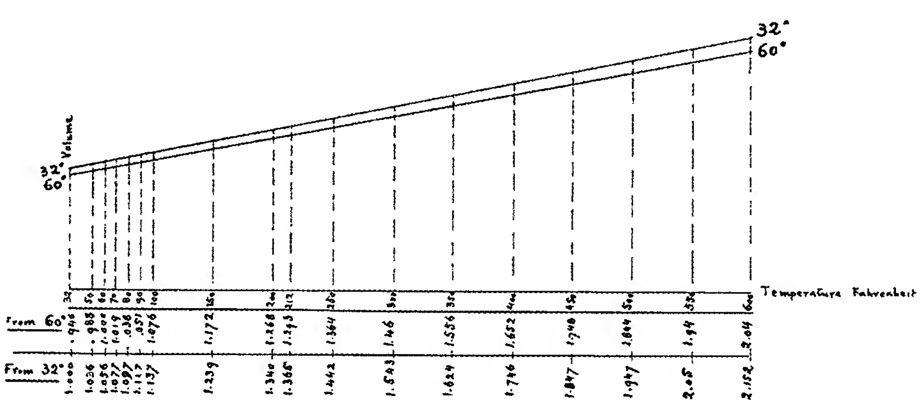


Fig. 6.--Expansion of One Cubic Foot of Air
from 32° and from 60°, to 600° F.

Class of Engine	Size (inches)	Temperature Fahrenheit of Air						Clearance compared to capacity of Single or of H.P. Cylinder	Cutoff in Fraction of Stroke	Temperature F. of Reheating to exhaust at 32° F. in each cylinder		
		Entrance			Exhaust							
		Single	Compound		Single	Compound				Single	Compound	
			H.P.	L.P.		H.P.	L.P.				H.P.	L.P.
Slide Valve		60			+7.5			.07	5/8	87		
Automatic Cutoff:												
Single		60			-80			.05	1/4	213		
Compound	9½&14½×10½		60	-31		-31	-113	.05	7/16		136	148
	10½ & 16 × 12		60	-31		-31	-113	.05	7/16		136	148
	12 × 1×13½		60	-31		-31	-105	.05	7/16		136	134
Corliss:												
Single		60			-84			.03	1/4	221		
		60			-103			.03	1/5	256		
Compound	10 & 15 × 30		60	-61		-61	-136	.03	1/3		180	145
	12 & 18 × 36		60	-61		-61	-136	.03	1/3		180	145
	14 & 22 × 36		60	-61		-61	-143	.03	1/3		180	159
	14 & 22 × 42		60	-61		-61	-143	.03	1/3		180	159

Fig. 7.--Air Engines
Terminal Temperatures with Cold Air, and Amount of Reheating

Several systems of reheating have been used. If the only object was to keep the exhaust ports from being blocked by ice, this could be done by just heating the exhaust ports with some source of heat, such as a lamp, or an injection of steam or hot water. But if such a source of heat is handy, it can be used to far better advantage in heating the air, either in the cylinder or before entering it.

One method of reheating consists of injecting a spray of warm water into the cylinder. The air absorbs the water's heat, cooling the water. Fig. 8 gives the weight of water at various temperatures that has to be supplied, for each pound of 60° F. air fully expanding from various pressures, so that the exhaust temperature will be 32° F.

Air pressure (psig)	B.T.U. required per lb. of air	Pounds of water per lb. of air, at water temperature:		
		75° F.	100° F.	150° F.
70	59.0	1.37	0.86	0.50
80	62.8	1.46	0.92	0.53
90	66.2	1.54	0.97	0.56
100	69.2	1.61	1.02	0.60

Fig. 8

A better method is to inject steam instead of hot water into the cylinder. The advantages of this system are, first that steam is in a gaseous state and mixes more readily with air than even finely atomized water, and besides, the condensation of the steam gives up its latent heat, which increases considerably the heating of the air.

A comparison of this process with the previous one can readily be made. Assuming that a spray of water at 212 °F. is injected into the cylinder, each pound of water will give up 180 B.T.U. before it is cooled to 32 °F.

But, taking steam at atmospheric pressure, i.e., also at 212° F., 1 lb. of steam, in the process of condensation, will abandon 966 B.T.U., its latent heat of vaporization, besides the 180 B.T.U. as above, making a total of 1146 B.T.U.

Air pressure, psig	B.T.U. required for each lb. of air	Lbs of steam at 212° per lb. of air
70	59.0	.051
80	62.8	.055
90	66.2	.059
100	69.2	.0604

Fig. 9

Fig. 9 gives the weight of steam at 212 °F. required for each pound of air to prevent its temperature from falling below 32° F. at complete expansion.

Similar calculations could be made to maintain the exhaust temperature at any given point. Besides, the use of steam keeps the walls of the cylinder wet, and while water alone is a poor lubricant between metallic surfaces, it facilitates the action of the regular lubricants, and is also favorable to the tightness of the piston packing.

It will readily be seen that both these methods prevent the formation of ice in the exhaust ports; their good effect is still more pronounced if the cylinder is provided with a jacket, into which hot air is circulated.

Air can also be reheated before being admitted into the cylinder. Various designs of heaters are used for this purpose, the air generally passing through a system of pipes heated by an interior furnace, a flue being provided for the passage of the hot gases on the outside of the pipes before they reach the chimney. And as air, on account of its bad conductivity, does not easily take up heat from the metallic sides of the pipes, it is expedient to inject in the pipes a small quantity of water which absorbs the heat more readily and penetrates with the hot air into the cylinder.

Another method of heating is to place a lamp or gas jet within the air pipe. The use of coal or wood is not advisable in this case, as grit and cinders would be carried by the current of air into the engine.

Reheating by electricity was still in an experimental state when air engines were being used in industry. The Thomas Register at the library has a section on appliances manufactured for heating compressed air. It should be mentioned that electric resistance heating is 100% efficient.

The ambient interheater is the best way to increase the volume of air, because the added energy is free and there is no high level heat or energy source involved.

The table giving the temperatures of exhaust in cold air work, also gives the temperatures at which air should be reheated prior to its admission to the single engines, or to each cylinder of the compound engines, in order to exhaust at 32° F.

These temperatures are moderate, and can be obtained with hot water, or low pressure steam. If the heating is done by passing the air through heated pipes, the fuel consumption will be very small, as practice shows that 1 lb. of coal gives the air from 8,000 to 10,000 B.T.U. in a properly designed heater.

To utilize the full benefit of reheating, and of air expansion in compound engines, an early cutoff is very desirable. This can be accomplished by reheating to 350° F., before the air enters each cylinder, and Fig. 10 shows the amount of free air required for various horsepowers under this condition. A comparison with Table Fig. 16 will show the marked advantage of this arrangement.

Size of Engine (inches)	**R.P.M.**	**Piston Speed (ft./min.)**	**CFM Free Air**	**Brake Horse-power, H.P. Cyl.**	**Point of Cutoff (Stroke = 1)**	**Temperature F. in both Cylinders**		**Gauge Pressure (psig)**		
						Initial	Final	Initial	Inter-mediate	Final
9½ & 14 × 24	112.5	450	444	50	.52	300	170	70	22.9	2
12 & 18 × 30	90	450	888	100	.52	300	170	70	22.9	2
13¼ & 20 × 30	90	450	1110	125	.52	300	170	70	22.9	2
13¼ & 20 × 36	75	450	1332	150	.52	300	170	70	22.9	2

Fig. 10: Free Air at 14.7 psia and 60° F.consumed per minute in

COMPOUND CORLISS AIR ENGINES PROPERLY OPERATED

- Brake horsepower is taken as .85 of indicated horsepower.
- Clearance in both cylinders is assumed to be 3% of theoretical cylinder capacity.
- Cylinders jacketed for hot air.

First Stage 2" Diameter	**Second Stage 2-1/2" Diameter**	**Third Stage 3-1/4" Diameter**	**Fourth Stage 4" Diameter**
100	45	20	4
150	84	34	8
200	104	46	17
250	180	80	40
300	190	100	51
350	220	115	53
400	232	126	64

Fig.11.--Pressure intake to each cylinder,
Four-stage Terry Miller engine prototype, psig.

The performance data in Fig.11 are from Air Powered Cars by Terry Miller. (Joplin, Missouri, 1983) His four-stage prototype engine uses air without cutoff. It is evident from this table that his engine is attaining a lot of expansion, despite the fact that it admits air at full pressure throughout the stroke. I attribute this to a combination of two causes: 1: The hose and valve supplying air to the first stage cylinder are only 1/4"; by choking off the air supply to the engine, perhaps the air is not entering the cylinder fast enough to keep the cylinder full behind the piston. This could

have the effect equivalent to cutoff, in an unregulated way, especially if the engine is being run toward the low end of its speed range. 2: There is no reheating used before any of the four stages of expansion, except for the small amount of ambient heat absorbed through the cylinder walls and the walls of the long 2" pipes used to store air between stages. With proper heat exchangers installed between stages, the air would be raised in temperature and pressure.

Technical information on compound expansion engines--such as proportioning the cylinder areas--is available in the sources such as those listed below. Although the information is on engines designed for the use of steam, it should be applicable to air also, except for those portions relating to condensing engines.

- <u>Heat and Heat Engines</u>, William C. Popplewell, Manchester: Technical Publishing Co., 1897, Chapter XXIX.
- <u>Mechanical Engineer's Pocket-Book</u>, William Kent, 1903.

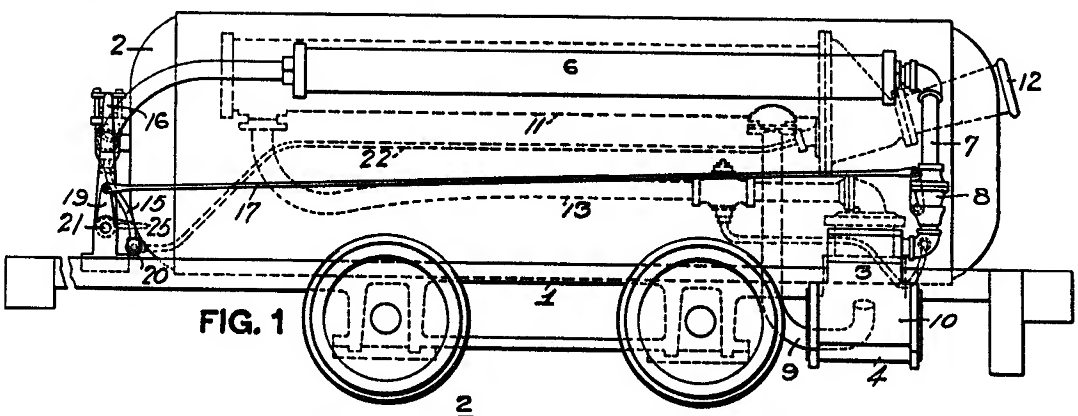
Chapter 3: The Most Efficient Air Engines Ever Built Commercially

U. S. Patent No. 979,165, Compound Compressed Air Engine, Patented Dec. 20, 1910, by Charles B. Hodges, assignor to H. K. Porter Co. of Pittsburgh, Pennsylvania.

(excerpted and paraphrased by the editor)

Object of invention: to provide means for carrying the air used for reheating the compressed air over the exposed surfaces of the inter-heater between the high pressure engine and the low pressure engine and to control the same in connection with the operation of the engines through its main or throttle valve.

Comprising: high and low pressure engines, interheater, throttle valve controlling the supply of air to the engine, measns to induce air over the surfaces in the interheater, a valve controlling the supply of compressed air to induce such current, lever mechanism controlling both the throttle valve and the current inducing valve.



Side view of an air powered locomotive

Numbered Components, Figures 1-3:

1, engine truck
2, main air reservoir tank
3, high pressure engine
4, low pressure engine
6, auxiliary reservoir
7, pipe from auxiliary reservoir 6, to valve box of the high pressure engine
8, main or throttle valve located in pipe 7
9, exhaust pipe from high pressure cylinder 10 to interheater
10, high pressure engine cylinder
11, interheater, supported on main tank 2; a shell-and-tube type heat exchanger; the tubes in the interheater provide an extended heating surface for the air from the high pressure cylinder
12, ejector discharge nozzle shrouding end of interheater; compressed air is supplied to the ejector to induce a strong current through the tubes of the interheater;

this air is drawn from any suitable part of the apparatus containing air under pressure

13, pipe from interheater 11 to the valve box of the low pressure cylinder 14

14, low pressure engine cylinder

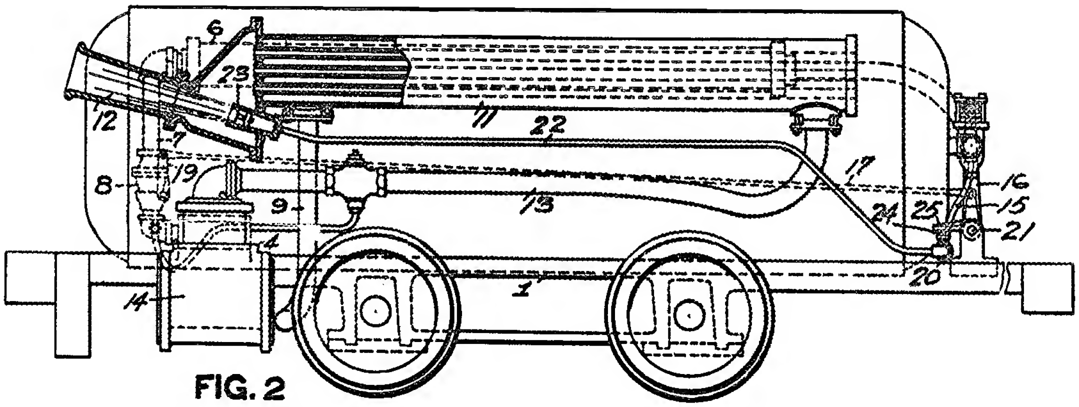


FIG. 2

Other side view, partly broken away

15, pipe from supply pipe to the auxiliary reservoir 6 into the cab close to the throttle valve lever 16

16, throttle valve lever

17, rod linking throttle valve lever 16 to throttle valve 8

19, lever operating throttle valve 8

20, air jet controlling valve on pipe 15, close to the shaft 21

21, shaft of the throttle lever 16

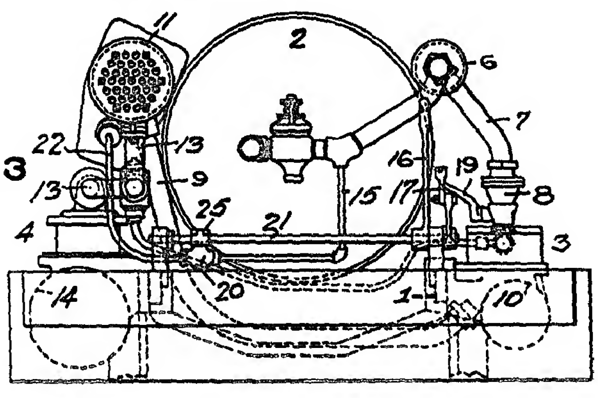
22, pipe from pipe 15 to nozzle 12, communicating with the air jet 23

23, air jet discharging into nozzle 12 to induce a draft of atmospheric air through the interheater and over the exposed surfaces of the tubes therein

24, stem of air jet controlling valve 20 extending up through the valve body close to the throttle lever shaft 21

25, auxiliary arm of the throttle lever shaft 21 extending over the valve stem 24, to control valve 20

FIG. 3



End view of valve mechanism for controlling throttle and air jet valves

Operation of the Engine:

The compressed air from the auxiliary reservoir **6** passes through the high pressure cylinder when the throttle valve is opened; The air expands in the high pressure cylinder, and its temperature is lowered much below atmospheric temperature. In order to increase its volume by reheating, the cold expanded air is carried through the interheater where it is exposed to a large amount of tubing surface area, the tubes being warmed by the atmosphere passing through

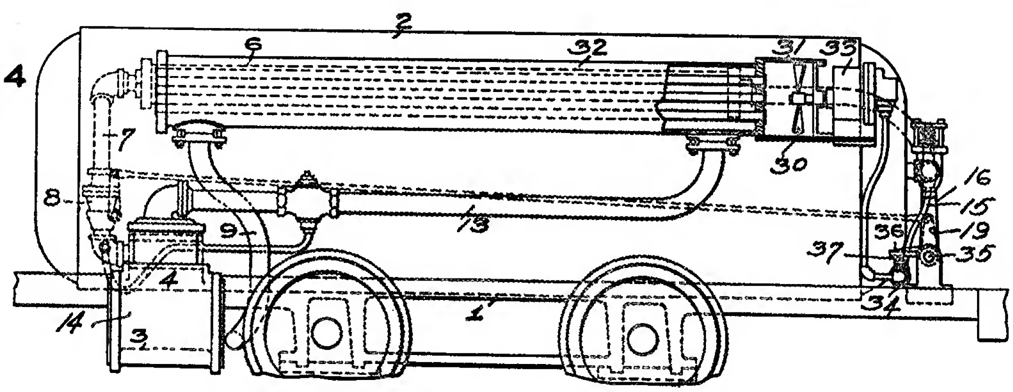
them. The ambient heat reheats the cold compressed air and increases its volume, after which the compressed air passes to the low pressure cylinder where it further expands and is exhausted.

The throttle lever valve is arranged to open the air jet valve in proportion to the opening of the throttle valve. It thus gives full control by the operation of one lever to the engine. In this way, the volume of air used to induce atmosphere into the interheater is in proportion to the amount of compressed air passing through to be reheated, and when the throttle is closed, the air jet for induction of atmosphere is also closed.

Numbered Components, Figure 4:

30, fan
31, tubular extension of interheater housing fan
32, interheater
33, air motor driving fan
34, valve like valve 20 above, to control the supply of air to the air motor 33; this valve is located close to the main throttle lever shaft 35
35, main throttle lever shaft
36, auxiliary arm of shaft 35, extending over valve stem 37
37, valve stem

FIG. 4



Modification in which the air draft through the interheater is induced with a fan.

Related patents by C. B. Hodges: 868,560, October 15, 1907; 953,334, 953,335, and 953,336, March 29, 1910; 1,024,778, April 30, 1912.

The Triple Expansion Air Engines of Europe

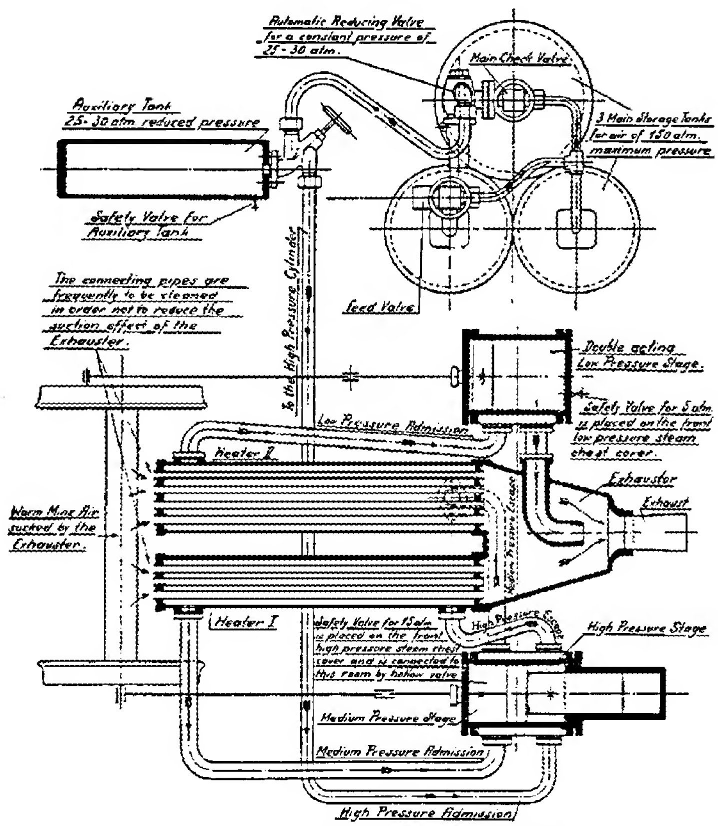


FIG. 3.—EXPLANATORY DIAGRAM OF TRIPLE-EXPANSION COMPRESSED-AIR LOCOMOTIVE WITH DOUBLE INTERMEDIATE HEATING.

The Iron and Coal Trades Review, June 5, 1925

The compound, ambiently reheated air engine became the most popular air engine not only in the American coal fields, but in those of Europe as well. In one coal field in Germany alone, there were 624 of these locomotives in use at one time.

The Europeans improved on Hodges' invention by adding a third stage to the engine, and absorbing ambient heat before all three stages. While the American compound air engine got 30% more range between fillups by the use of interheaters, the European version got up to 60%.

Since World War II, very little has been published about these engines, or any other air engines.

The other day I asked a retired mechanical engineer what engineering students are taught about compressed air. His response: "Very little..."

For more information on these engines--most of which was published in French and German--see the bibliography.

Chapter 4: Air Engine Valves

Valves and Valve Operation

The following section on steam engine valves is included because commercial air engines of the past were built along the same principles as steam engines, and were made by the same companies. Exhibits of working steam engines, especially if displayed indoors, are run on compressed air, even at the Smithsonian Institution. Some of the comments made in these articles will not apply to air, especially regarding water and condensation.

These expansion engines were operated by valve gear linkages, or reversing gear, that could vary the cutoff under different loads, up to the point of reversing the engine; therefore, no forward/reverse gearbox was needed. Whether or not you use similar valves and valve operating systems, you should be familiar with the concepts involved. Modern spool valves sold for the purpose of controlling pneumatic actuating cylinders could be adapted for these reversing gear; they are like the balanced piston valves, or cylindrical slide valves, mentioned below. Spool valves can be used off-the-shelf if only a simple cam is to be used as an operator. If cutoff is to be used, a three-way valve must be used on each end of a double-acting cylinder so that the intake and exhaust ends of the cylinder can be controlled independently. A single double-acting cylinder can be used to control both ends of a double-acting cylinder only if the air is to be used throughout the whole stroke without cutoff; the intake and exhaust events, must mirror each other. Examples of cam shapes for both 3-way and 4-way spool valves are included in this chapter, as are catalog descriptions of spool valves, and some examples of reversing gear diagrams.

Some alternative valve operating systems for spool valves include air pilot operators, and solenoid operators. Information on these systems can be obtained from the valve manufacturers. Advantages of the pilot operated valve are the flexibility of positioning, since components can be connected with hoses or pipes instead of moving linkages. Advantages of the solenoid operated valve are similar to the above, but the disadvantage is that electricity is being introduced into what could be a purely mechanical system. An example of an electrical valve operating system can be seen in the Leroy Rogers patent in the chapter on Extending Range. The mechanical cam or reversing gear is the most foolproof system, but robs more power from the engine to run.

Spool valves need to be lubricated unless the engine is to be run very slowly, in which case the grease that the valves are lubricated with in the factory should suffice. Oil misters are available for pneumatic appliances but would violate the air engine's potential as a totally non-polluter and non-user of petroleum products. If misters are used once, they must be used continuously as the oil washes the factory grease out of the valves. If an engine block is to be cast and/or machined, oil passages for a pumped oil supply can be included; this would be better than misting the air supply. The best solution is to make the spools from a self-lubricating material, such as teflon or viton, and use similar material for the seals, which are generally attached to the housing of the valve, rather than the spool.

If using a simple cam rather than a reversing gear, a cam follower must be used. This is a small wheel at the end of the valve operating linkage that contacts the periphery of the cam. The cam follower can be a ball bearing, or if no linkage is interposed between valve and cam, the cam-operated valve comes with its own cam follower. The diameter of the follower should be as small as possible in relation to the cam; if it is too big, the upward slope of the cam will pinch and bend the operating linkage instead of pushing it straight in line with the spool.

This is not a complete course on valve design or valve operation. If you want to learn more, or if you want to find an expert, here are some sources of information: a model engine or antique engine machinist, collector, or club; old books on steam engines, available in larger libraries, used bookstores, or as reprints from Lindsay Publications and others; magazines put out for model engineers, which contain ads for companies that sell steam engines and models; books on model engine design.

Engine Valves

(from Rogers Erecting and Operating, William Rogers, New York: Audel, 1907.)

The distribution of steam within the cylinders of an engine is controlled by valves of varying forms, which fall into three broad classifications; (1), Slide valves, which travel to and fro over a plane or curved surface, and regulate the passage of the steam through ports in that surface; (2), Rotary valves, in the cylindrical form, which vibrate within a cylindrical seat, as in the Corliss engine, also admitting or exhausting the steam past their edges; (3), Disc or drop valves, of forms more or less like an ordinary stop valve, which are raised from or lowered upon their seats to regulate the passage of the working fluid, such as are fitted to large pumping engines.

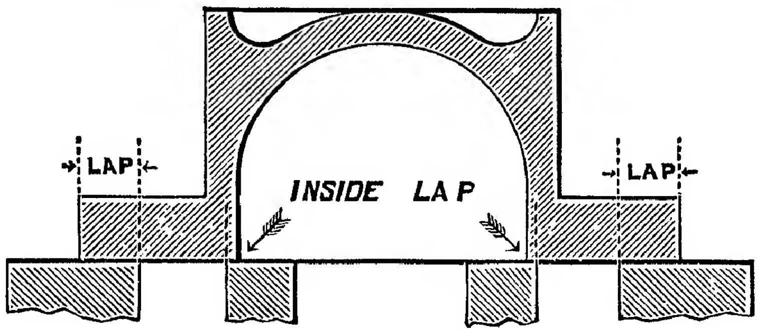


Fig. 454.--VALVE WITH OUTSIDE AND

The following four figures are intended to exhibit the elements of slide-valve design, showing lap, lead, and travel. The proportioning of slide valves has been a matter of experiment since the days of Watt. The majority of the engines that have ever been made have been fitted with this form of- valve.

Slide-Valve Design.

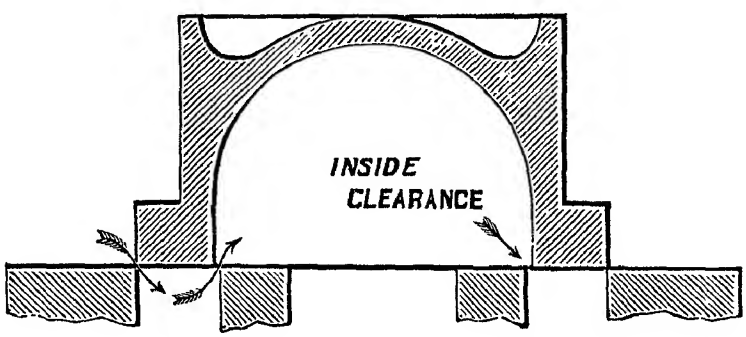


Fig. 455.--VALVE WITHOUT LAP AND WITH INSIDE CLEARANCE.

Taking first the common slide, or D-valve as it is termed from its "D" section, its parts and properties will be readily seen from Fig. 454. Should the outer edges of the valve coincide with the edges of both steam ports, or be "line and line," as it is termed, such as shown in Fig. 455, steam will be carried to the end of the stroke.

To procure expansion, lap is added to the outer edges of the valve as in Fig. 454; the eccentric, which in the former case was 90° in advance of the crank,.is moved through a further angle so that the edge of the valve is in the position shown in Fig. 456, giving an

opening to steam before the piston has completed its previous stroke,--this pre-admission is termed the lead of the valve.*

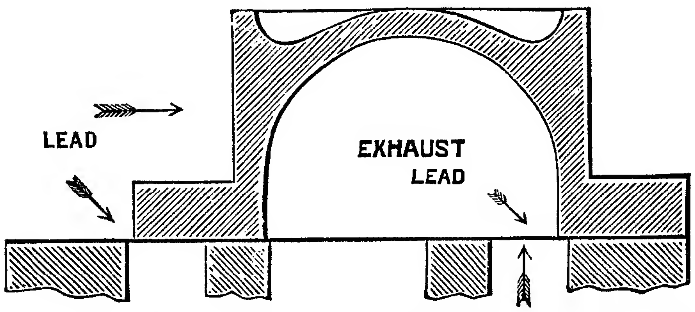


Fig. 456.--VALVE SHOWING OUTSIDE AND INSIDE LEAD.

The amount by which the other port of the cylinder is open to exhaust, as shown in Fig. 456, may be termed exhaust lead.

The full movement of the valve is known as its travel, and fig. 457 represents its position at either extremity of the stroke.

The travel of the valve is, of course, equal to twice the throw of the eccentric, and also equals twice the lap + the amount of opening of each port to steam. In designing a valve gearing, the necessary port opening is first determined, and all the other proportions calculated from it as a basis.

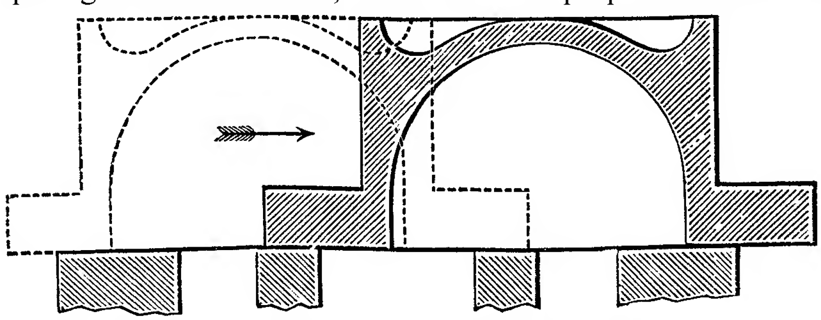


Fig. 457.--VALVE SHOWING MAXIMUM TRAVEL.

Owing to the angular advance necessitated by the lap, communication is established between the cylinder and the exhaust passage through the internal cavity of the valve at a point before the completion of the pressure stroke.

This early opening to exhaust is known as release, and the exhaust continues until the valve has reached a point corresponding to that of release in the opposite direction, when the exhaust is closed, thus occasioning what is known as compression or cushioning. The steam is imprisoned in front of the advancing piston, thus forming a cushion to absorb the inertia of the moving parts, bringing the piston gradually to rest before it starts on its next stroke.

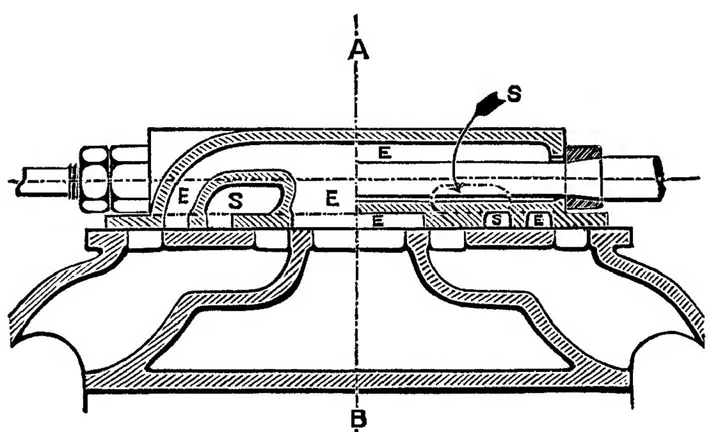


Fig 458.

With slow-moving engines it is necessary to increase the amount of the compression by adding inside lap to the exhaust edges as in Fig. 454, but with high-speed engines it is frequently found difficult to get the steam out of the cylinder fast enough, and so these edges are pared away, forming what is known by engineers as minus or negative inside lap, or occasionally termed inside clearance. This opens communication between the two ends of the cylinder at certain points of the stroke, but that is not important with the high speed.

* NOTE.--This must not be confused with what is known by some engineers as the *lead of the eccentric*, this latter dimension being more properly known as *angular advance*.

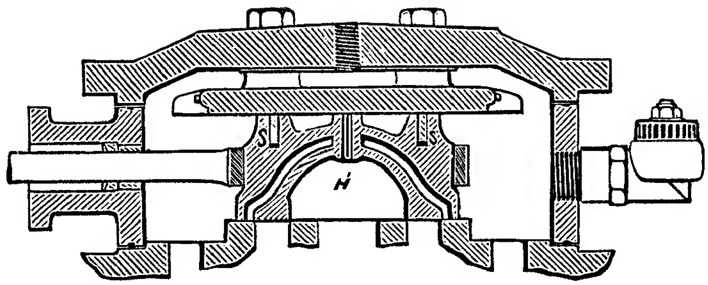


Fig. 459.

As the travel of the valve is the direct measure of the work of the eccentric, engineers try to shorten it as much as possible. This is accomplished by providing more than a single admission for the steam, single-ported valves being regarded as unfit for cylinders above the moderate diameter of 24 inches. Fig. 458 represents the double-ported valve which is used for medium-sized engines, a treble port being used for cylinders of still larger diameters.

On account of the extent of surface exposed to steam pressure by these large valves, recourse is often had to balancing, or relieving as much of the back of the valves as possible from this pressure which imposes great friction on the valve. Rings or planed strips are held up against a plate or the steam chest door and prevent the access of steam to the area which is enclosed by these means. A cock communicates either with the atmosphere or condenser to prevent any accumulation of pressure within the balanced surface.

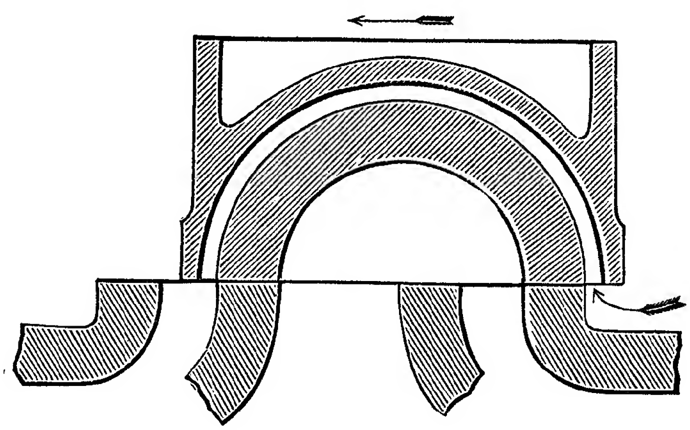


Fig. 460.

The typical balanced valve, illustrated in Fig. 459, has found much favor among locomotive engineers, but like all this class of valve, requires careful design and excellent workmanship to make it effective. It will be noticed that a cored hole communicates from the exhaust cavity to the balanced area, thus ensuring the pressure of exhaust steam alone on the back of the valve.

A simple means of obtaining double admission with but a single port is seen in the Trick or Allen valve, shown in, Figure 460, much used on locomotives, small marine cylinders, and stationary engines of moderate power. A certain amount of balancing is also claimed for it. The steam passes to the cylinder port from the opposite end of the valve through the passage cast in its back, as well as past its normal edge. The process of exhausting is the same as with a D valve.

Owing to difficulties attending the removal of the exhaust steam from the cylinder, it is impractical to attempt an earlier cut-off than about half stroke with an ordinary slide valve and eccentric. To give economical rates of expansion, two valves are employed, each having a separate eccentric; the expansion or cutoff valve being a grid or plate, working on the back of the main valve, which serves as its seat, the steam ports being passages through the main valve, which latter controls exhaust alone. In such a case the governor acts upon the expansion valve through a link, shortening the travel and cut-off as the load lightens.

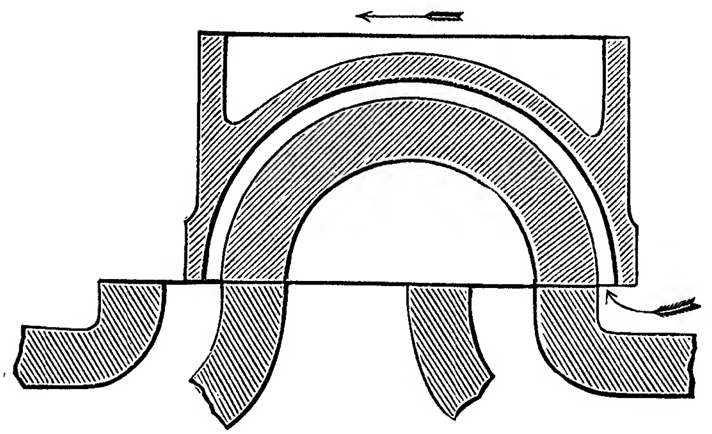


Fig. 461.

The Meyer valve illustrated in Fig. 461 is employed where necessary to vary the expansion by hand. The expansion valve consists of two flat plates controlled by a right and left hand screw on the valve stem; the tail end of the stem is carried through a stuffing box, and is rotated by means of a hand wheel, shorter cut-off being obtained by turning the stem so that the plates become further apart, which is the same as increasing the lap.

The piston valve, Fig. 462, is a cylindrical slide valve working in a seat curved to suit it. It is consequently balanced, and is considered the least objectionable form of valve that can be used; it cannot leave its face when dirt or grit is deposited upon it, and its chief defects are that unless carefully designed and fitted, it is not as steam tight as ordinary valves.

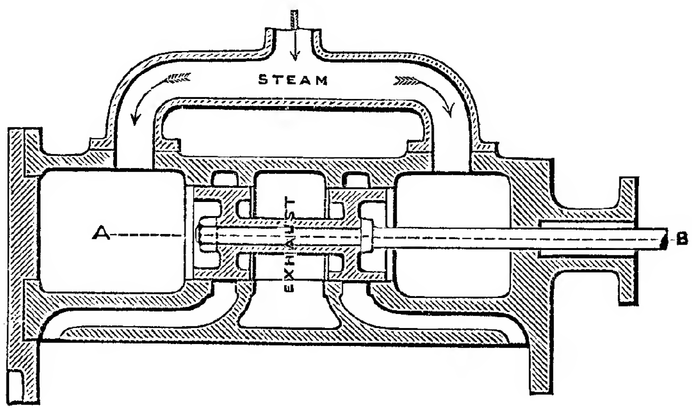


Fig. 462.

The Corliss valve, shown in Fig. 463, is the outcome of an effort to produce a valve gear which would have the following advantages:—(1), minimum of power to actuate the gear; (2), smallness of clearance spaces; (3), adaptability to close governing; (4), good steam opening combined with quick cut off and free exhaust. It avoids many of the disabilities of the slide valve and is a favorite gear on account of the sharp outline of its indicator diagram. Some of the largest and best known engine-builders in the world have modified and improved the original design of valve and operating mechanism until it has reached a state of great perfection.

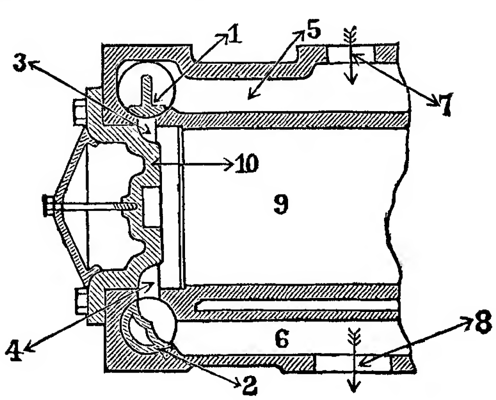


Fig. 463.

In the illustration, Fig. 463, steam enters the cylinder casing by the opening for the steam pipe flange (7), and flows around the cylinder barrel in the annular passage (5), thus jacketing the cylinder It gains admission past the steam valve (1), through the admission port (3), into the bore of the cylinder (9). After performing its work upon the piston the steam passes through the exhaust port (4) and exhaust valve (2), into the exhaust passage (6), finally escaping to the atmosphere or condenser through the eduction pipe (8); the cylinder cover (10) is not jacketted in this instance.

In Fig. 464, these valves are shown in perspective

on an enlarged scale, (1) being the steam valve and (2) the exhaust valve. The recesses a, cut across the face of the circular end of the valves, are to receive a T-shaped head of the valve stems, which transfers the rotary motion of the latter to the valves, and still allows the valves to be withdrawn from their respective chambers by removing the covers on the front side of the engine.

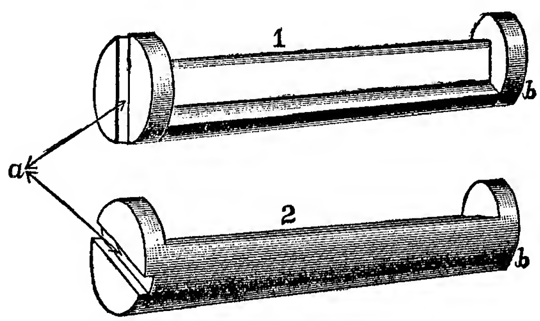


Fig. 464.

It also enables the valves to leave their seats, if forced by water or over-pressure, and to follow up near without bending the valve stem. The steam valve is riding upon the port, which connects the steam chest (5) with the cylinder, and is held to its seat by steam pressure, while the exhaust valve is held to a port connecting exhaust chamber (6) with the exhaust valve chamber; thus the steam pressure always holds it to its seat.

Table Showing Lap and Lead of Valves of Corliss Engine.

Cylinder Diameter in inches.	**Wrist Plate on its Centre.**		**Steam Lead, Engine on Centre.**
	Steam Lap.	**Exhaust Lap.**	
8, 10 & 12.	3/16”	1/32”	1/32”
14, 10, 18 & 20.	1/4”	1/16”	1/32”
22, 24, 26, 28 & 30.	5/16”	3/32”	3/64”
32, 34,&36.	3/8”	1/8”	1/16”

NOTE.--The drop valve, originally used altogether with large pumping and winding engines, has been long in favor with Swiss and German engineers, and in many directions is fast supplanting the more delicate Corliss gear. Its range of adaptability extends from large central station engines indicating 10,000 H. P. down to the fast-running motor car with its 1000 revolutions per minute, and is evidently a type of valve to be reckoned with in all future engineering progress. This valve is not illustrated.

Link Motion.

Many classes of engines, more especially those which are self-propelling or employed for hoisting purposes, need some means for the reversal of the motion in which the engine travels. This is effected by a most ingenious mechanism operating in connection with the eccentric of the engine known as the reversing gear, of which there are several, such as the Allan, the Walschaert, link motion.

There is still another known as the shifting link motion, otherwise called the "Stephenson." All these are mechanical devices by which the crank rotation of an engine may be reversed at the will of the engineer, with only the loss of time required to overcome the momentum of the moving parts, and by which a like speed and power may be developed in a reverse direction. This problem of reversal, so simple upon first thought, required many years in its solution. Much has been written and published upon the subject.

An eccentric, when directly connected to the valve stem, always leads the crank in the direction of rotation; reversal may therefore be secured by shifting the eœentric around the crank shaft from one side of the crank to the other, and giving it an equal advance in the opposite direction, or by the equivalent method of placing a separate eccentric either side of the crank.

This arrangement of two eccentrics and gearing forms a link motion, a general type of which is shown in Fig. 465.

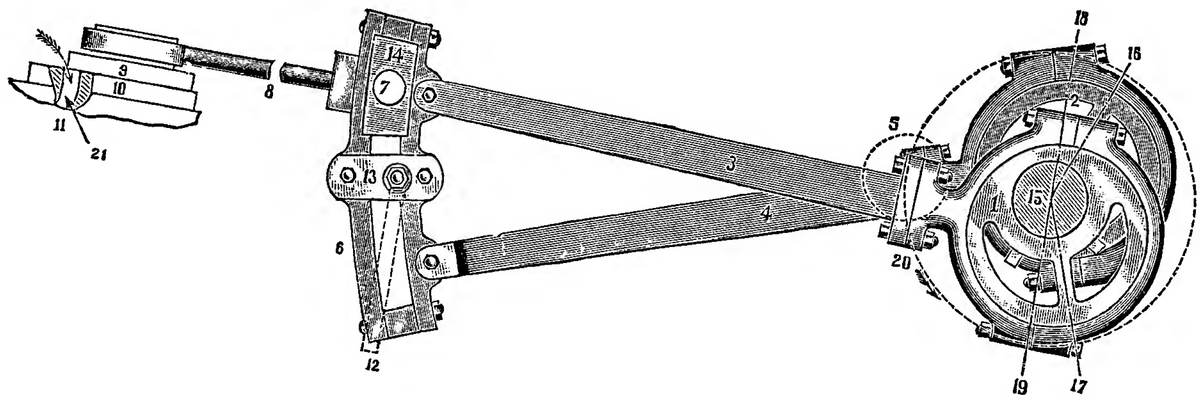


Fig. 465.

The saddle and saddle pin, 13, afford attachment for the suspension or lifting links, 12, by means of which the link is raised and lowered. This is effected from the engineer's platform through the agency of levers and rocking shafts not shown in the illustration.

The slide valve, 9, is surrounded by a yoke formed in the valve spindle, 8, the latter being formed with jaws at its outer end to fit the link, 6. The pin, 7, passes through both jaws of the spindle, and the link block, 14, which latter is of case-hardened steel or phosphor bronze, and slides in the radial slot formed in the link. This block, 14, thus forms a constant attachment between the slide valve and the eccentrics.

To reverse motion, the link is lifted, until the other eccentric rod is in line with the link block; the middle of the link or midgear is the neutral position, where no steam is admitted. At any intermediate position the valve has a reduced travel, caused by a compound motion due to both eccentrics, and this allows variable expansion by simply shifting the link a little in either direction.

Two eccentric sheaves, 1 and 2, are keyed upon the crank shaft, 15, on opposite sides of the crank pin, which is indicated by a dotted circle, 5. The general direction of motion is shown by arrow heads on the larger dotted circle, 20, which represents the crank pin path.

The lower eccentric, 1, leads the crank pin by 109½° in the running direction, as shown by its centre line, 17; it is therefore the go ahead or forward eccentric. Its companion, the go astern or backward eccentric, 2, is seen from the position of its centre line, 16, to lead the crank by 111° when the engine is revolving in the opposite direction. These angles, which constitute the angular advance, may be measured by reference to the line, 18-19, which makes a right angle with the crank pin on either side.

The eccentric rods, 3 and 4 are attached to either end of the shifting link or quadrant, 6, the forward eccentric rod being attached to its upper extremity for mechanical convenience, the gear as illustrated being in its normal or forward position.

Air Valve Sizing

(from Norgren Directional Control Valves, Catalog NC-80, 1981, p.123-124.)

Most manufacturers' catalogs give flow rating C_v* for the valve, which was established using proposed NFPA standard T3.21.3. The following tables and formulas will enable you to quickly size a valve properly. The traditional, often used, approach of using the valve size equivalent to the port in the cylinder can be very costly. Cylinder speed, not port size, should be the determining factor!

BORE SIZE D (IN)	PUSH BORE F (SQ IN)	BORE SIZE D (IN)	PUSH BORE F (SQ IN)
3/4"	.44	4"	12.57
1"	.79	4-1/2"	15.90
1-1/8"	.99	5"	19.64
1-1/4"	1.23	6"	28.27
1-1/2"	1.77	7"	38.48
1-3/4"	2.41	8"	50.27
2"	3.14	10"	78.54
2-1/2"	4.91	12"	113.10
3-1/4"	8.30	14'	153.94

TABLE 1: CYLINDER PUSH BORE AREA F FOR STANDARD SIZE CYLINDERS

The following Cv calculations are based upon simplified formulas which yield results with acceptable accuracy under the following standard condition:

Air at a temperature of 68°F (20°C)

Absolute downstream or secondary pressure must be 53% of absolute inlet or primary pressure or greater. Below 53%, the air velocity may become sonic and the C_v formula does not apply. To calculate air flow to atmosphere, enter outlet pressure p_2 as 53% of absolute inlet pressure p_l. Pressure drop Δp would be 47% of absolute inlet pressure. These valves have been calculated for a $C_v = 1$ in Table 3.

* This is not the same C_v used elsewhere in this book to signify specific heat at constant volume.

NOMENCLATURE:

B	Pressure drop factor	
C	Compression factor	
C_v	Flow factor	
D	Cylinder Diameter	(IN)
F	Cylinder Area	(SQ IN)
L	Cylinder Stroke	(IN)
p_1	Inlet or Primary Pressure	(PSIG)
p_2	Outlet or Secondary Pressure	(PSIG)
Δp	Pressure differential (p_1 - p_2)	(PSID)
q	Air flow at actual condition	(CFM)
Q	Air flow of free air	(SCFM)
t	Time to complete one cyl. stroke	(SEC)
T	Absolute temperature at operating pressure. Deg R = Deg F + 460	(°R)

Valve Sizing For Cylinder Actuation—Direct Formula

$$C_v = \frac{F \times L \times C}{B \times t \times 29}$$

Example: Cylinder size 4" Dia. x 10" stroke. Time to extend: 2 seconds. Inlet pressure 90 PSIG. Allowable pressure drop 5 PSID. Determine C_v.

Solution:	Table 1	F = 12.57 SQ IN
	Table 2	C= 7.1
		B = 21..6

$$C_v = \frac{12.57 \times 10 \times 7.1}{21.6 \times 2 \times 29} = .7$$

Select a valve that has a C_v factor of .7 or higher. In most cases a 1/4" valve would be sufficient.

It is considered good engineering practice to limit the pressure drop Δp to approximately 10% of primary pressure p_1. The smaller the allowable pressure drop, the larger the required valve will become.

After the minimum required C_v has been calculated, the proper size valve can be selected from the catalog.

Valve Sizing With C_v = 1 Table

(For nomenclature see above)

This method can be used if the required air flow is known or has been calculated with the formulas as shown below:

INLET PRESSURE (PSIG)	COMPRESSION FACTOR C	PRESSURE DROP FACTOR B FOR VARIOUS PRESSURE DROPS Δp				
		2 PSID	5 PSID	10 PSID	15 PSID	20 PSID
10	1.7	6.5				
20	2.4	7.8	11.8			
30	3.0	8.9	13.6	18.0		
40	3.7	9.9	15.3	20.5	23.6	
50	4.4	10.8	16.7	22.6	26.4	29.0
60	5.1	11.7	18.1	24.6	29.0	32.0
70	5.8	12.5	19.3	26.5	31.3	34.8
80	6.4	13.2	20.5	28.2	33.5	37.4
90	7.1	13.9	21.6	29.8	35.5	39.9
100	7.8	14.5	22.7	31.3	37.4	42.1
110	8.5	15.2	23.7	32.8	39.3	44.3
120	9.2	15.8	24.7	34.2	41.0	46.4
130	9.8	16.4	25.6	35.5	42.7	48.4
140	10.5	16.9	26.5	36.8	44.3	50.3
150	11.2	17.5	27.4	38.1	45.9	52.1
160	11.9	18.0	28.2	39.3	47.4	53.9
170	12.6	18.5	29.0	40.5	48.9	55.6
180	13.2	19.0	29.8	41.6	50.3	57.2
190	13.9	19.5	30.6	42.7	51.7	58.9
200	14.6	20.0	31.4	43.8	53.0	60.4
210	15.3	20.4	32.1	44.9	54.3	62.0
220	16.0	20.9	32.8	45.9	55.6	63.5
230	16.7	21.3	33.5	46.9	56.8	64.9
240	17.3	21.8	34.2	47.9	58.1	66.3
250	18.0	22.2	34.9	48.9	59.3	67.7

TABLE 2: COMPRESSION FACTOR C AND PRESSURE DROP FACTOR B.

1. $$Q = .0273\frac{D^2 L}{t} \times \frac{p_2 + 14.7}{14.7} \quad \text{(SCFM)}$$

Conversion of CFM to SCFM

2. $$Q = q \times \frac{p_2 + 14.7}{14.7} \times \frac{528}{T} \quad \textit{(SCFM)}$$

Flow Factor C_v. (standard conditions) Proposed NFPA Standard T3.21.3

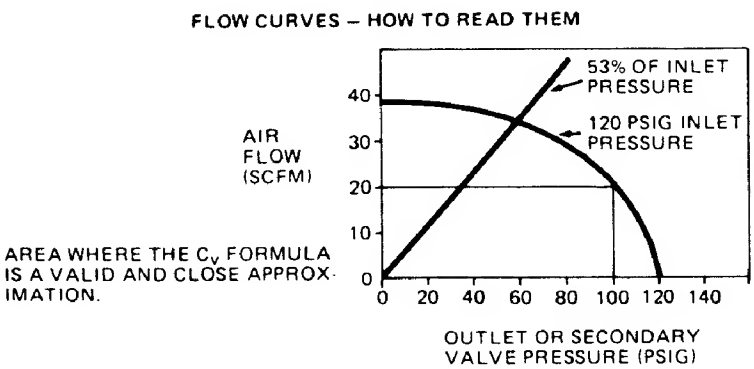
3. $$C_v = \frac{1.024 \times Q}{\sqrt{\Delta p \times (p_2 + 14.7)}}$$

Maximum pressure drop Δp across the valve should be less than 10% of inlet pressure p_1.

EXAMPLE 1: find air flow Q(SCFM) if C_v is known. C_v (from valve catalog) = 1.8
Primary pressure p_1 = 90 PSIG
Pressure drop across valve Δp = 5 PSID

INLET PRESSURE (PSIG)	AIR FLOW Q (SCFM) FOR VARIOUS PRESSURE DROPS Δp AT A $C_v = 1$					AIR FLOW Q (SCFM) TO ATMOSPHERE
	2 PSID	5 PSID	10 PSID	15 PSID	20 PSID	
10	6.7					12.0
20	7.9	11.9				16.9
30	9.0	13.8	18.2			21.8
40	9.9	15.4	20.6	23.8		26.6
50	10.8	16.9	22.8	26.7	29.2	31.5
60	11.6	18.2	24.8	29.2	32.3	36.4
70	12.3	19.5	26.7	31.6	35.1	41.2
80	13.0	20.7	28.4	33.8	37.7	46.1
90	13.7	21.8	30.0	35.8	40.2	51.0
100	14.4	22.9	31.6	37.8	42.5	55.9
110	15.0	23.9	33.1	39.6	44.7	60.7
120	15.6	24.9	34.5	41.4	46.8	65.6
130	16.1	25.8	35.8	43.1	48.8	70.5
140	16.7	26.7	37.1	44.7	50.7	75.3
150	17.2	27.6	38.4	46.3	52.5	80.2
160	17.7	28.4	39.6	47.8	54.3	85.1
170	18.2	29.3	40.8	49.3	56.0	90.0
180	18.7	30.1	42.0	50.7	57.7	94.8
190	19.2	30.9	43.1	52.1	59.4	99.7
200	19.6	31.6	44..2	53.4	60.9	104.6
210	20.1	32.4	45.2	54.8	62.5	109.4
220	20.5	33.1	46.3	56.1	64.0	114.3
230	21.0	33.8	47.3	57.3	65.5	119.2
240	21.4	34.5	48.3	58.6	66.9	124.0
250	21.8	35.2	49.3	59.8	68.3	128.9

TABLE 3: AIR FLOW Q(SCFM) FOR C_v = 1.



Flow through valve from Table 3 for C_v = 1:21.8 SCFM

$$Q = C_v \text{ of valve} \times \text{air flow at } C_v = 1 \text{ (SCFM)}$$

$$\underline{Q = 1.8 \times 21.8 = 39.2 \text{ SCFM}}$$

EXAMPLE 2: Find C_v if air flow Q(SCFM) is given.

Primary pressure p_1 = 90 PSIG

Pressure drop Δp = 10 PSID

Air flow Q = 60 SCFM

Flow through valve from Table 3 for C_v = 1:30 SCFM

$$C_v = \frac{\text{Air Flow Q(SCFM)}}{\text{Air Flow at } C_v = 1\text{(SCFM)}}$$

$$\underline{C_v} = \frac{60 \text{ SCFM}}{30} = \underline{2.0}$$

A valve with a C_v of minimum 2 should be selected.

EXAMPLE 3: Find C_v if air flow Q(SCFM) to atmosphere is given (from catalog).

Primary pressure p_1 = 90 PSIG

Air flow to atmosphere Q= 100 SCFM

Flow to atmosphere through valve from Table 3 for C_v = 1:51 SCFM

$$C_v = \frac{\text{Air Flow to atmosphere Q(SCFM)}}{\text{Air Flow to atmosphere at } C_v = 1\text{(SCFM)}}$$

$$\underline{C_v} = \frac{100}{51} = \underline{2.0}$$

Flow given in catalog is equivalent to a valve with C_v = 2. This conversion is often necessary to size a valve properly, since some manufacturers do not show the standard C_v to allow a comparison.

EXAMPLE 4: Find C_v if cylinder size and stroke speed is known, using the formulas 1 and 3.

Primary pressure = 90 PSIG
Pressure drop across valve 5 PSID
Cylinder size 4" DIA. × 10" Stroke
Time to complete stroke 2 sec.

$$Q = .0273\frac{4^2 \times 10}{2} \times \frac{85+14.7}{14.7} = 14.81 \text{ SCFM}$$

$$\underline{C_v} = \frac{1.024 \times 14.81}{\sqrt{5 \times (85+14.7)}} = \underline{.7}$$

Spool Valves I Have Used

Rexroth is one of many companies that manufacture spool valves for compressed air. The Rexroth Type "D" Pilotair valve was used by Terry Miller on all his air cars, and I've used them on my experimental engines. One of their best and most unique features is that they are made in segments held together with tie rods, and if you want the port to face a different direction you just loosed the tie rods, clock all the ports the way you want them, and you just saved yourself a design headache. Because of this versatility, I recommend these valves for at least the preliminary prototypes. They come in 1/4" and 1/2" port sizes, in many different configurations. For air engines I recommend valves with tapped exhaust (for compounding and/or mufflers), closed center (for cutoff), and cam-operators (for direct, reliable service.)

Another company that makes spool valves for air is Parker Hannifin in Richland, Michigan, phone 616-694-9411. Their Bulletin 0665-B1 describes the "HHB", a valve made specifically for non-lubed applications. The HHB is available in 3/8", 1/2", and 3/4" port sizes. All air car designers should think of ultimately eliminating the need for lubricating fluids in the air.

A few companies manufacture spool valves up to a 1" port size. For a comprehensive list of valve makers, consult the Thomas Register at the public library.

REXROTH TYPE "D" PILOTAIR VALVES

(from the Rexroth catalog SC-700, 1992, 1953 Mercer Rd., Lexington, KY 40511; call 606-254-8031 for a catalog or the nearest distributor of Rexroth valves)

INDEX AND DESCRIPTIONS

The Type "D" PILOTAIR Valve line includes the following basic valves:

Two-way Valve
Three-way Valve, Open Exhaust
Three-way Valve, Tapped Exhaust, Closed Center
Four-way Valve, Open Exhaust, Closed Center
Four-way Valve, Tapped Exhaust, Closed Center
Four-way Valve, Open Exhaust, Exhaust Center
Four-way Valve, Tapped Exhaust, Exhaust Center
Four-way Valve, Tapped Exhaust, Open Center

The above valves can be operated by any of the following operators, all of which have several variations of spring return and holding functions.

Lever
Button
Button, Panel Mounting
Cam
Air Pilot Cylinder
Solenoid
Pedal
Treadle
Low Pressure Pilot Cylinder

Select the type of valve operation required and then determine the type or types of operators to be used. Tabulations on pages 35 thru 41 list the piece numbers to be used for ordering the most commonly used combinations. Also include the complete description of the valve to eliminate the possibility of error.

Example: Piece Number PD4-31-1007, 1/2" Three-way Valve, Open Exhaust, Pilot Cylinder Operator "A" End, Cam Operator "B" End, No Return Springs (page 36).

See page 42 for ordering combinations not listed in these tabulations.

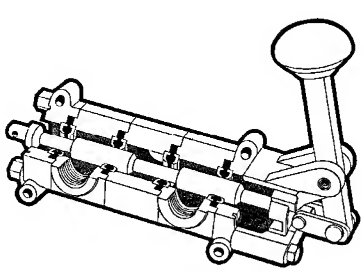
OPERATORS

Passages through the Type "D" PILOTAIR Valve are opened and closed by an operator or operators moving a spool to a fixed position at either end of its travel. Some valves have a third or center position midway between these two fixed positions. Any of the available operators may be used on either two- or three-position valves. The spring return functions, however, will vary according to the number of positions. Operators can be furnished with No Spring Return, Full Return Springs or Centering Springs.

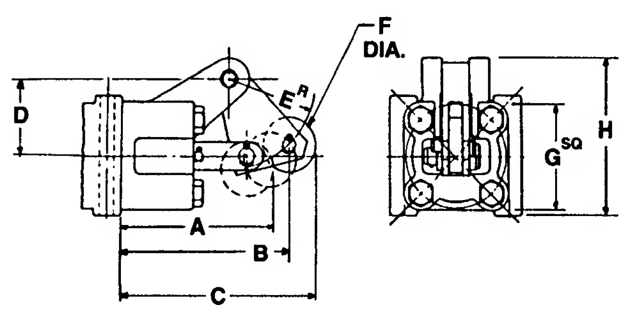
NO SPRING RETURN—Used on either two- or three-position valves. Operators with no spring return remain in position when the operating force is removed. Only manually-operated valves used singly can be used without return springs. Remote-controlled or mechanically-operated valves used singly must have return springs to return the spool for the next operation. When two operators are used on one valve, the spool is returned by the opposite operator. Lever or Button Operators without spring return may also be used with a detent kit on the opposite end.

FULL RETURN SPRING—Used on two-position valves. When the operating force is removed, the spool is returned to its normal extreme position. The spring may be a part of the operator or assembled on the opposite end of the valve, depending on whether the valve is normally-open or normally-closed.

CENTERING SPRINGS—Used on three-position valves. Centering springs hold the spool in its center position. This return function can be used on either single-operator or double-operator valves.



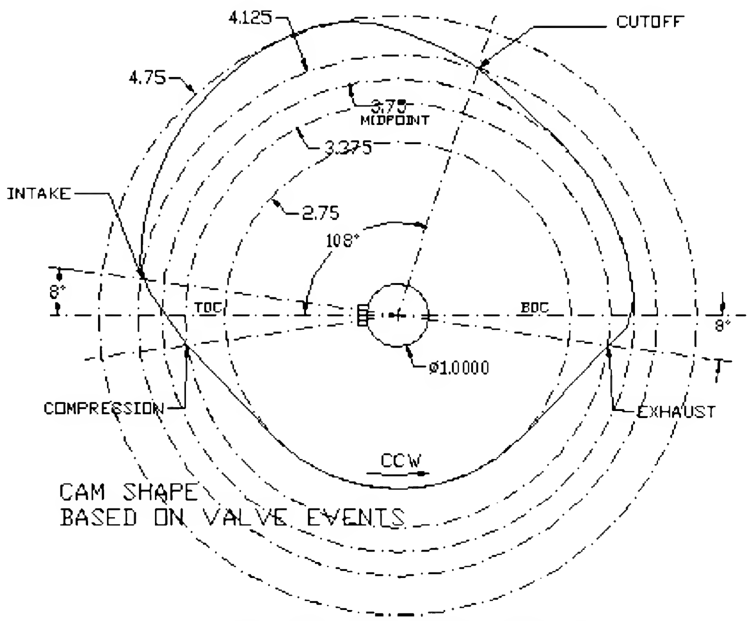
CAM OPERATOR



Sample Cam Shapes

The comments in this section regarding cams, valves, and cylinders are based on my limited experience and some may apply only to simple systems of operating engines with cams. If you want to design a reversible engine with variable cutoff, you'll need to study steam engine texts. The information in that field is extensive, and beyond the scope of this book, except for the summary included earlier in this chapter.

Cam For Three-way Spool Valves



Cam For Three-Way Spool Valves

This cam was designed for a two-stage engine I built by converting a two-stage Ace compressor from a WWII Liberty Ship. The single- acting pistons in this engine are horizontal and in line with each other, that is, their longitudinal axes are on the same line, making them 180° opposed on the same crankshaft, which is between them. This made it relatively easy to run the separate 3-way valves on the same cam; the cam followers are just mounted to contact the cam straight across from each other.

In order to get the piston clearance--port and pipe displacement between piston and valve--as small as possible, the valves are mounted on a deck directly above the cylinder ports which are in the heads at the opposite end of the engine. This was not close to the engine shaft, and rather than built a secondary cam shaft to get in close to the cam followers (wheels) that came with the valves, I interposed a linkage with a second cam follower that actually ran on the periphery of the cam, and this wheel was fixed at the end of the linkage. The other end of the linkage pushed the "cam follower" on the valve which did the actual valve operating. The linkage was in two parts, like your arm. The cam was on the main engine shaft. The axle of the follower wheel ran in a horizontal sliding bearing which was mounted in such a way to locate the two followers horizontally and directly across from each other. The follower is mounted in the end of the linkage "forearm" where your hand would be. The forearm extends approximately horizontally out toward the end of the engine and ends at an "elbow", a pivot that swings freely out in space. The "upper arm" begins at the elbow and extends upward to the "shoulder", a pivot mounted to the valve deck. The upper arm extends beyond this fixed pivot point and its upper edge is rounded to bear rollingly against the wheel on the valve operator. The valves are mounted in line with the pistons with their operators facing outwardly, toward the ends of the engine. The valve return spring pushes the spool and operator wheel outwardly towards the end of the engine. The upper end of the upper

arm pushes the spool in towards the center of the engine against spring pressure when the high lobe of the cam pushes the cam follower the opposite way.

The maximum travel of the spool is .75", but is used at .625" to avoid bottoming it out at either end of its stroke. Because of the linkage arrangement; the cam has a mechanical advantage or leverage of 3 to 1 over the valve return spring it resists. The distance from the elbow pivot to the shoulder pivot is exactly three times greater than the distance from the shoulder pivot to the point where the upper arm contacts the cam operator. I wanted to keep the forearm approximately horizontal and the upper arm approximately vertical so they would be at approximately right angles to each other, so the interposition of the linkage would not rob the cam of the torque needed to resist the valve return spring, which is very strong. The disadvantage of an expansion engine is its relatively large size and weight in relation to its power output; the advantage is its efficient use of air compared to anything you can buy off the the shelf.

The first version of this engine worked well for a short time, but it became apparent that something was wrong with the cam setup. The cam appeared to be pinching against the follower wheel, trying to bend it instead of pushing it horizontally. Research pointed out that the cause of this defect was too small of a difference between the cam radius and the cam follower radius. The cam radius was 4.75", and the follower was a 2" skate wheel. A new cam, as shown in the drawing above, is being made, and the skate wheel will be replaced with a 1" diameter ball bearing. Other than that, no changes will have to be made except for longer mounting brackets to attach the smaller cam follower to the end of the forearm.

The cam dimensions are listed below:

2.75, the low cam radius

2.75 + .625 = 3.375; the cam's exhaust range of travel = .625; this is 3 × the same distance as traveled by the valve

3.375 + .75 = 4.125; the cam's closed center range of travel is .75, or 3 × the same distance as traveled by the valve; notice that the closed center range of travel is not shaved off to .625 ,but is a full .75; this is why the distance from the low cam to the high cam is greater than .625 × 3

4.125 + .625 = 4.75; the cam's intake range of travel = .625; this is 3 × the same distance as traveled by the valve

3.375, the midpoint of the cam radii; corresponds to the midpoint of the valve's closed center range of travel; this is the base point from which the other dimensions start

108° = 180° × 60% cutoff; 180° is the full power stroke, or half of the full 360° cycle; intake is cut off at 60% of the power stroke, 108° from TDC

TDC, top dead center or beginning of the power stroke

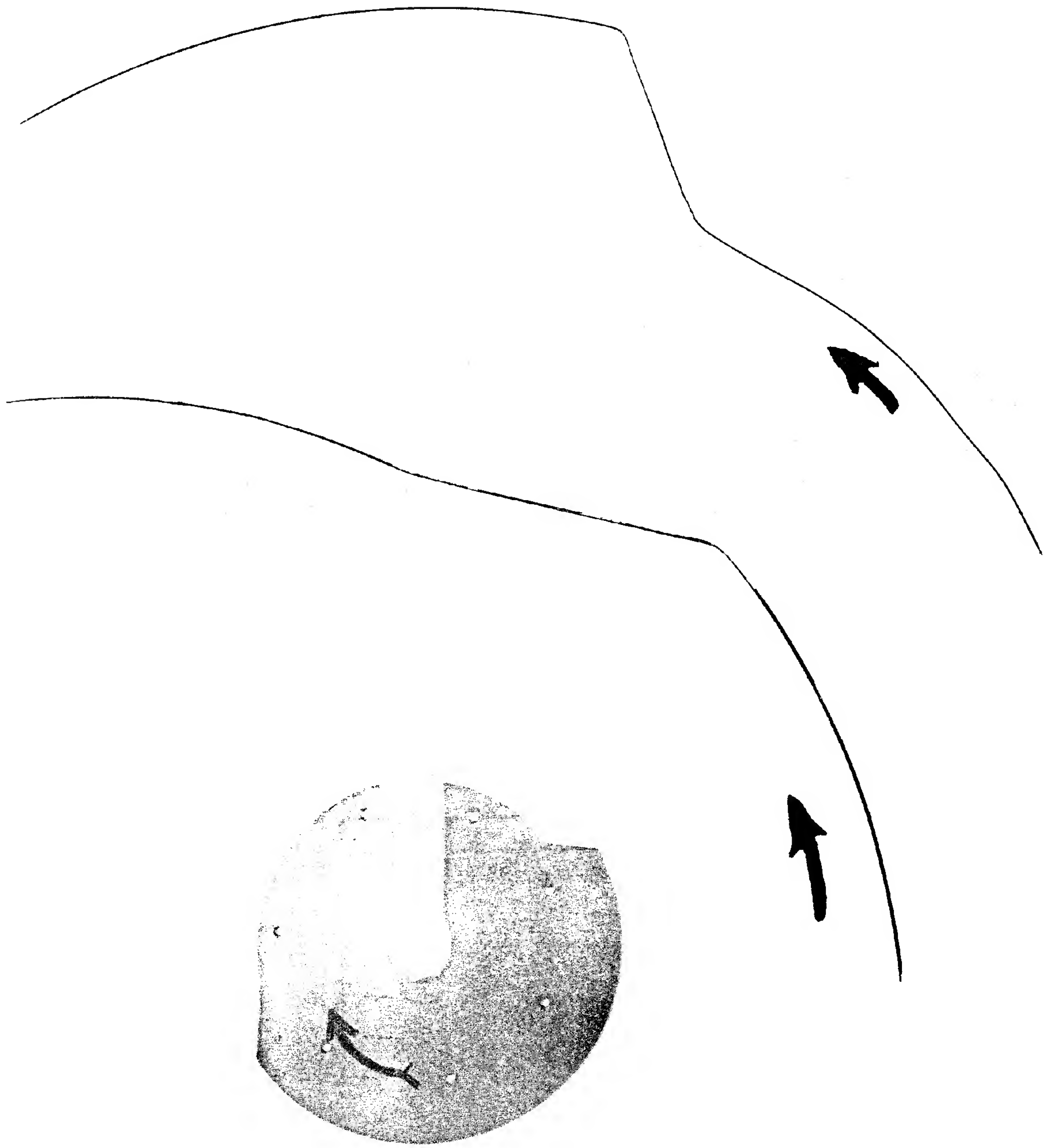
BDC, bottom dead center of beginning of the exhaust stroke

8°, angular advance; intake and exhaust do not begin until the crankshaft is definitely past the point of being equally willing to go either way; the dimension 8° was chosen without the aid of actual knowledge and may be far from ideal; if the eccentric (cam) were retarded instead of being advanced, the engine would run backwards, which is the principle of the reversing gear mentioned earlier in this chapter

Cutoff, the point at which the valve enters its closed center position where intake ceases so that the air already in the cylinder can expand more fully; 60% cutoff doesn't provide full expansion, but provides more power for the size of the engine and a more even impulse to the shaft

Compression, the point at which the exhaust ends; slightly before the end of the piston's exhaust stroke, causing a cushioning effect to slow the piston down in preparation for the change in direction at the end of the stroke
CCW, counter-clockwise shaft rotation
1.000, shaft diameter

Cam for Four-way Spool Valves



Cam for Four-way Spool Valves

(from Air Powered Cars, by Terry Miller, Joplin, Missouri, 1983):

"Dimensions of this cam are; High cam 11" dia. Low cam 9" dia."

With a 1" difference between the high and low cam radii, there must be .25" clearance between the low lobe and the cam operator when the spool is fully extended by the return spring; the valve travel is only .75". I can think of no other reason why the difference between the high and low cam radii should be more than .75".

Nevertheless, the engine does work well, and I drove "Air Car One" several hours in 1985.

The cylinders in your car's engine are single-acting; they only push one way. A double-acting cylinder, common in fluid power, is supplied with air through ports at each end in turn, which pushes the piston first one way, then back the other; it's essentially two pistons in one. In some of the triple-expansion engines, and in some compound (multi-stage) compressors, the two ends of the piston and cylinder are two different diameters, providing for two stages of expansion or compression in one cylinder. This saves space.

The important difference between a cam for a 3-way valve and a cam for a 4-way valve is that the closed center range of valve travel is barely used, except to provide a very short transition between intake and exhaust, for negligible cutoff and compression. There can be no true cutoff during the main part of the intake stroke, because the same valve is operating both ends of the double-acting valve at the same time. Because of this the valve events as determined by the cam shape must be the same for intake and exhaust; if the intake were cut off at 30% on one end of the cylinder, the exhaust would be cut off at 30% on the other end.

In normal industrial use, a double-acting cylinder would be controlled by a 4-way valve. This is because the air is not used expansively, so intake and exhaust take place through their entire halves of the cycle. A 3-way valve has fewer ports, and is used to control a single-acting cylinder. Since the intake lobe and exhaust lobe are being used at different parts of the cycle, the two halves of the cam can be different shapes, allowing for the use of cutoff. You can use one cam to operate two 3-way valves as long as the two cam followers are positioned 180° from each other, that is, directly across from each other with the engine shaft--or cam shaft, if they are separate shafts--exactly midway between the two cam followers. This enables the operation of a two-cylinder single-acting engine, either one-stage or two, or the operation of a double-acting cylinder with two 3-way valves instead of one 4-way valve, thus allowing the use of cutoff. It would also be conceivable to place four single-acting cylinders at 90° around the cam, for a radial engine. If the cylinders were the same diameter, the engine would be single-stage; if different diameters, it would be compound. Terry Miller's prototype is a 4-stage compound engine, and uses four different sizes of double-acting cylinders operated in series without cutoff by four 4-way valves. The advantage to using cutoff in a compound engine is that more of the air's internal energy is used, and more cold is produced, so more ambient heat can be absorbed for use as free fuel. The advantage to using intake through the full stroke is that the engine is smaller for its output and is simpler to design and cheaper to build. The power impulse is also smoother; with cutoff a flywheel is necessary to even out the impulses to the shaft.

A design issue to consider when using double-acting cylinders is that the rod normally extends out of only one end of the cylinder. Since piston force = piston face area (in^2)× pressure (psig), the rod eliminates part of the potential push area from its end of the cylinder. With an unequal push coming from each end of the cylinder, the engine will run somewhat less smoothly than it should; if the engine runs at a low rpm like Terry Miller's, this doesn't matter. But if you want to try and get some speed out of your engine, you might consider buying or building double-rod cylinders so that the force is the same on each side of the piston. The disadvantage to this is that the extra rod takes up more space, and you'll have to think of something for the extra rod to do. If you're building a self-fueling engine, one rod could turn the crankshaft or operate the crankshaft substitute (torquerack or swash-plate), and the other rod could drive a compression cylinder for putting air back into the tank through the equalizer, or booster compression cylinder for scavenging the equalizer tailpipe. See the chapter on Maxwell's Demon for the definition of "equalizer" and "scavenging."

Valves Used in the Hardie Compressed Air Locomotive

(excerpts from "Compressed Air Cars in New York," Street Railway Journal, August 4, 1900)

The valve chest of the engine cylinders contains two valves, one the distribution or main valve, and the other the cut-off valve. These valves are operated in such a manner that any degree of cut-off can be obtained, as illustrated by the indicator diagrams. Compressed air has this advantage over steam, that it does not condense during expansion in the engine cylinder. Therefore, expansion may be carried with economy clear down to atmospheric pressure. To do this in a steam engine would cause what is known as cylinder condensation. Steam engines are compounded principally to reduce this cylinder condensation to a minimum, but this is not necessary with compressed air.

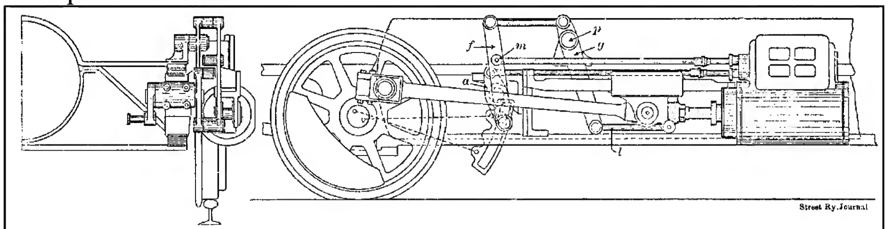


Fig. 4.—Diagram of Engine Cylinder, Showing Valve Gear.

It was necessary to contrive a valve mechanism which would not be too complicated to operate, and yet obtain the best results. The valve mechanism which is attached to these motors is illustrated in Fig. 4. The usual Stephenson link motion is used to operate the main valve, but on the outside of the link there is an arm *a*, looking down as well as up. At the lower end of the lower arm is attached the lower end of a floating lever, *f*. The upper end of lever *f* receives a reduced motion, which is the opposite of the piston, through the lever *g* and link *l*, lever *g* being pivoted by a bracket attached to the frame at the point *p*. It will be observed that the lower end of floating lever *f* receives a motion directly the opposite of the main valve, and that its upper end has a motion directly the opposite of the piston rod. This lever *g* is attached to the cut-off rod at the point *m*, and gives to the cut-off valve a motion which is the resultant of the other two. The consequence is that when the main valve is traveling in full gear, the cut-off valve is also traveling at its longest stroke, and gives the earliest cut-off. When, however, the link motion is "cut back" so as to reduce the motion of the main valve, it gives a later cut-off. The indicator cards, shown [below], indicate the effect of this. The first notch indicates the full travel of both valves, and each succeeding notch a reduced travel of both valves, showing a later cut-off. It will be observed that the latter grades show some terminal pressure which produces an audible exhaust, but these grades of cut-off are used only for starting the motor, and the lever is immediately moved to a position corresponding with either of the first three notches, according to the power required, which depends upon the loads and grades. It will be observed while cutting off at the earlier notches there is a freer exhaust, which will more readily free the cylinder when going fast. In the ordinary locomotive the cutting off is effected by the link motion only, with the result that the exhaust openings are diminished.

'...There is every reason to expect that these new motors will be successful, because Mr. Hardie has had more experience in this line than any other engineer in the United States, and has made the subject a special study for years. He has, morover, held many responsible positions, and stands high in the profession. His standing among engineers is well expressed in the following extract from *Compressed Air*: "His mechanical ideas are marked by much individuality, the elements of simplicity being prominent. It is doubtful if any one has had as much experience as Mr. Hardie in pneumatic traction, and he is the acknowledged authority on the subject."...'

RESULTS OF DISTRIBUTION OBTAINED BY HARDIE VALVE GEAR FOR THREE POSITIONS OF LINK, WITH 3.16 IN. INSIDE AND OUTSIDE LAP OF MAIN VALVE AND 11/16 IN. NEGATIVE LAP OF CUT-OFF VALVE ADMISSION PORTS 2½ INS. × 5/8 INS. CYL 6½ INS. × 12 INS.

FIRST POSITION
Main Valve (Full) Travel 2 in.
Cut-off Valve Travel 2 in.

Crank Angle	Cut-off Valve Opening		Main Valve Opening		Piston Travel	
	Front	Back	Front	Back	Front	Back
°	Inches					
0	15/16	7/8	7/32	7/32	0	0
10	21/32	19/32	3/8	3/8	.11	.08
20	11/32	5/16	½	½	.42	.31
30	0	0	5/8	21/32	.94	.67
40	–¼	–¼	11/16	¾	1.61	1.20
50	–½	–15/32	¾	17/32	2.46	1.83
60	–11/16	–23/32	¾	7/8	3.69	2.62
70	–7/8	–29/32	¾	15/16	4.44	3.48
80	–1-1/32	–11/16	¾	15/16	5.47	4.45
90	–1-3/32	–1-1/8	11/16	7/8	6.53	5.48
100	–1-1/8	–1-1/8	21/32	25/32	7.55	6.54
110	–1-1/32	–1-3/32	½	21/32	8.54	7.56
120	–15/16	–31/32	13/32	½	9.69	8.62
130	–25/32	–27/32	9/32	5/16	10.17	9.54
140	–5/8	–11/16	1/8	5/32	10.81	10.39
150	–13/32	–15/32	–1/32	–1/32	11.66	11.06
160	–1/8	–7/32	–7/32	–7/32	11.70	11.58
170	1/8	3/32	–13/32	–3/8	11.93	11.89
180	15/32	13/32	–9/16	–19/32	12.00	12.00

SECOND POSITION
Main Valve Travel 1½ in.
Cut-off Valve Travel 1-11/16 in.

Crank Angle	Cut-off Valve Opening		Main Valve Opening		Piston Travel	
	Front	Back	Front	Back	Front	Back
°	Inches					
0	1	1-1/16	5/32	5/32	0	0
10	13/16	7/8	¼	9/32	.11	.08
20	9/16	19/32	11/32	3/8	.42	.31
30	5/16	3/8	7/16	7/16	.94	.67
40	1/8	5/32	15/32	15/32	1.61	1.20
*50	–3/32	–1/16	9/16	19/32	2.46	1.83
60	–¼	–¼	9/16	19/32	3039	2.62
70	–7/16	–13/32	9/16	5/8	4.44	3.48
80	–9/16	–9/16	½	9/16	5.57	4.45
90	–21/32	–5/8	7/16	½	6.53	5.58
100	–11/16	–21/32	3/8	7/16	7.55	6.54
110	–21/32	–5/8	5/16	3/8	8.54	7.56
120	–19/32	–9/16	¼	9/32	9.39	8.62
130	–½	–7/16	3/32	1/8	10.17	9.54
140	–3/8	–5/16	–1/32	–1/32	10.81	10.39
150	–9/32	–5/32	–9/64	–5/32	11.33	11.06
160	–1/8	–1/32	–¼	–9/32	11.70	11.58
170	1/16	5/32	–3/8	–13/32	11.93	11.89
180	5/16	3/8	–½	–17/32	12.00	12.00

THIRD POSITION
Main Valve Travel 1 in.
Cut-off Valve Travel 1½ in.

Crank Angle	Cut-off Valve Opening		Main Valve Opening		Piston Travel	
	Front	Back	Front	Back	Front	Back
°	Inches					
0	1-1/16	1-1/8	1/8	7/64	0	0
10	15/16	1	5/32	5/32	.11	.08
20	13/16	29/32	7/32	7/32	.42	.31
30	21/32	¾	¼	9/32	.34	.67
40	17/32	19/32	¼	5/16	1.61	1.20
50	3/8	7/16	¼	5/16	2.46	1.83
60	¼	5/16	¼	5/16	3.39	2.62
70	1/8	5/32	7/32	5/16	4.44	3.58
80	0	0	3/16	5/16	5.47	4.45
90	–1/16	–1/16	5/32	9/32	6.53	5.58
100	–1/8	–3/32	3/32	3/16	7.55	6.54
110	–5/32	–3/32	1/64	1/8	8.54	7.56
120	–5/32	–3/32	–1/16	1/32	9.39	8.62
130	–1/8	–1/16	–1/8	3/32	10.17	9.54
140	–3/32	0	–3/16	5/32	10.81	10.39
150	0	3/32	–9/32	9/32	11.33	11.06
160	1/16	3/16	–11/32	3/8	11.70	11.58
170	1/8	9/32	–13/32	7/16	11.93	11.89
180	7/32	5/16	–15/32	15/32	12.00	12.00

*Cut-off at 47°. Average piston travel, 1.91 in.

Main cut-off and compression crank angle, 148°	Main cut-off and compression crank angle, 138°	Main cut-off and compression crank angle, 117°
Lead angle of crank—front, 12°; back, 12°	Lead angle of crank—front, 13°; back, 13°	Lead angle of crank—front, 18°; back, 18°
Point of cut-off, not including clearance,	Point of cut-off, not including clearance, 1/6.29	Point of cut-off, not including clearance, 1/2.42
Point of cut-off, including clearance, 1/9.54 of	Point of cut-off, including clearance, 1/5.19 of	Point of cut-off, including clearance, 1/2.29 of
Greatest port opening, 7/16 in.	Greatest port opening, 3/8 in.	Greatest port opening, 9/32 in.
Relative travel of main and cut-off valves, 3-5/8	Relative travel of main and cut-off valves,	Relative travel of main and cut-off valves, 1-5/8

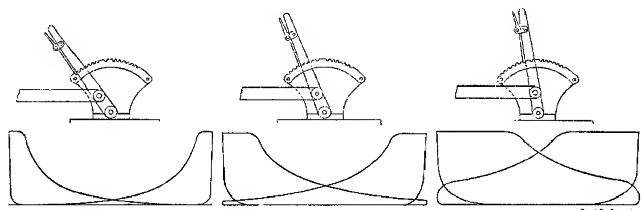
The variation of cut-off is effected by changing position of reverse lever (see sketches), and grades of cut-off are obtainable between those given in the tables, the earliest grades being when lever is full over, so as to give valve full throw. In this position there is also the greatest amount of lead.

Cut-off, including clearance, means $\dfrac{\text{piston travel at cut-off} + \text{clearance}}{\text{stroke of piston} + \text{clearance}}$: clearance in cylinder, 4%.

Inside and outside lap being equal, main valve cut-off and compression take place at the same point.

The greatest port openings noted above are taken at the point where cut-off and main valve openings are equal, the cut-off closing while the main valve is opening. In the earlier grades this takes place near beginning of stroke when piston is moving slowly, and in the later grades when motor is moving slowly. There is always ample exhaust opening.

Readings were taken at equal crank angles for convenience, but valves would be set to cut-off at equal piston movements from each end of cylinder.



Chapter 5: Vehicle Power Requirements

*"The Force is **within** you. Force **yourself!**"*
—H(arrison) Ford

The Power Needed

Torque and Horsepower Relationships

Before I use an engineering formula, I like to know where that formula came from. Seldom is a complete explanation included in an engineering book, so what I end up doing to satisfy myself of a writer's knowledge is to compare at least two sources of the same information. If I don't quite understand some things about each of the sources, by looking at the same concept from the perspective of another engineer's explanation, I can find out what is being said, and why. This is especially true in the case of constants, which are often inserted into an equation with no explanation of how they were derived.

The automakers aren't eager to enlighten us as to how little power is required to get us down the road; they provide us with huge, powerful gas engines rated in the 100s of horsepower, when all we really need is a little torque to get started and very little to keep going, just enough to overcome friction; like a flywheel, a moving car stores part of the work that was invested in getting it going as momentum and kinetic energy. The internal combustion engine is such a hot-headed, overstuffed feedbag that it can't produce torque till it's spitting wasted heat out in every direction and spinning at over 1000 RPM.

Source 1: (Fluid Power Data Book, 9th ed., Dallas: Womack Educational Publications, 1991, p. 26, 34.)

> Horsepower required = brake horsepower = Torque × RPM ÷ 63,024.
> 63,024 is derived from 5252 × 12 since in this case Torque (T) is expressed in inch-lbs. If torque is expressed in ft-lbs, HP = (T × RPM) ÷ 5252.
> Inch units are used here because torque is derived from wheel radius (see below).

Source 2: (Motor Vehicle Engineering Guide, James William Fitch, 3rd ed., Bellingham, 1956, p. 43-46.)

> Torque is twist that produces or tends to produce rotation (T = turning or twisting work.)
> Torque is work that is done rotationally.
> Mathematically, torque and work are treated the same; power can be determined if you know the time element through which a certain amount of torque (or work) is done.

Source 2:

$$\text{Horsepower} = \frac{\text{Torque in ft–lbs} \times \text{RPM}}{\text{5252 conversion factor}}$$

This formula is derived from the prony brake equation (see illustration):

$$HP = \frac{2\pi R \times RPM \times F}{33{,}000}$$

That is, regarding prony brake measurement of engine power, HP = flywheel curcumference × RPM × brake force in lbs. at rim of flywheel ÷ 33,000 ft-lbs/min, the conversion factor for 1 horsepower.

THE PRONY BRAKE

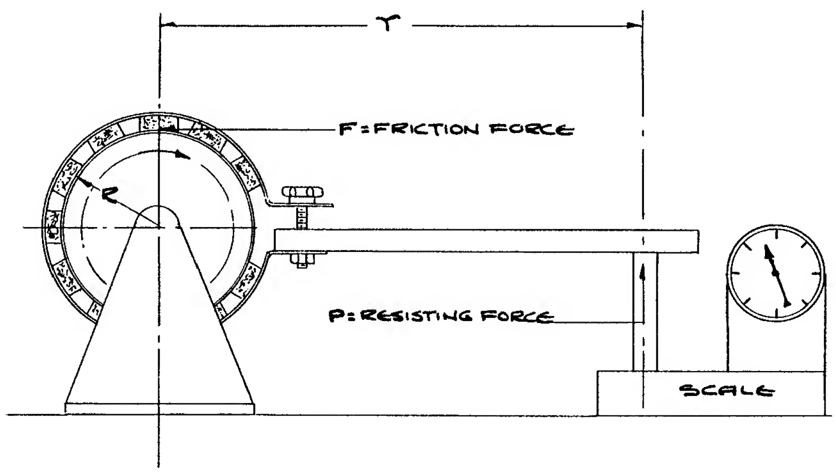


Fig. 1

Brake force is converted into heat at rim of flywheel.

That is, force × distance = power; distance is comprised of rim cirmcumference × revs.

Therefore, Torque is force at rim of flysheel × flywheel radius; T = F × R.

Also:

Torque is the resisting force of the scale (P) × distance from power shaft to resistance force (Y); T = P × Y.

If T = F × R and T = P × Y, and $HP = \frac{2\pi R \times RPM \times F}{33{,}000}$,

then by substituting T for R × F in the horsepower formula,

$$HP = \frac{2\pi \times T \times RPM}{33{,}000}.$$

$$\text{Since } \frac{2\pi}{33{,}000} = .0001904 = \frac{1}{5252},$$

$$HP = \frac{T \times RPM}{5252}.$$

Therefore, 5252 is the constant for the constant for converting between horsepower, torque, and RPM, when torque is in ft-lbs:

$$HP = \frac{T \times RPM}{5252}$$
$$T = \frac{HP \times 5252}{RPM}$$
$$RPM = \frac{HP \times 5252}{T}$$

The Forces to Overcome

Rolling Resistance

This is the resistance caused by contact between the tire and the road. Rolling resistance varies depending on the nature of the two surfaces in contact.

Rolling resistance of pneumatic tires on paved roads varies from 10 to 37 lbs. of force for each 1000 lbs. of vehicle weight;

22 lbs. is the maximum on asphalt;

20 lbs. is OK for an average figure, therefore, for a car under normal driving conditions,

$$\boxed{F_R = \frac{20W}{1000},}$$

where:

F_R = rolling resistance, lbs. force
W = vehicle weight, lbs.

Acceleration Force

The momentum of the vehicle is equivalent to the constant force that would bring it to rest in one second by resisting its movement,

$$M = \frac{WV}{g},$$

where:

M = vehicle momentum
V = vehicle velocity, ft/sec
g = the acceleration of gravity = 32.16 ft/sec/sec.

From this quantity is derived the force needed to accelerate to a given speed in a given time.

Acceleration of a vehicle involves weight, accelerating force, and time:

$$\boxed{F_A = \frac{VW}{gT}}$$

where:

F_A = accelerating force, lbs
V = final velocity, ft/sec
T = time duration that force is active, seconds.

g converts weight into mass; $F_A = M \div T$.

Grade Resistance

Grade resistance is the extra pull needed to keep the vehicle in constant motion up a hill; it is expressed in rise per linear distance traveled, as a percentage. It can be a negative number, if the car is going downhill, but this doesn't concern us.

$$\boxed{F_A = GW}$$

where:

F_G = grade resistance, lbs force

G = grade, %.

For example, a 10 ft. rise in 100 ft. traveling distance is 10/100 = .10 = 10% grade; think of it as 10 % of straight up, since force is a measurement of lifting straight up; because of gravity, weight is a resisting force in a straight-down direction, so grade resistance (like all resistances to vehicle motion) is equivalent to extra vehicle weight, and a 10% grade adds 10% of the vehicles weight at a force to overcome.

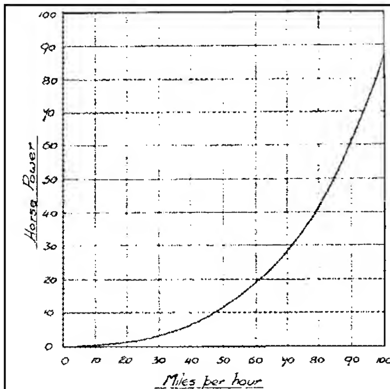


Fig. 2.--Horsepower required to overcome wind resistance at various speeds, based on effective fraontal area of 12 ft^2; for example, if the car had a frontal area of 24 ft^2, the horsepower requirement would be twice what the chart shows

Wind Resistance

Wind resistance is important only in vehicles moving over 20-30 mph. This phenomenon can be blamed on the fact that the formula for determining wind resistance includes the *square* of the car's speed.[*]

$$\boxed{F_W = A\left(mph^2\right).0025}$$

where:

F_W = wind resistance

A = vehicle effective frontal area, ft^2

mph = vehicle speed, mph

.0025 = a constant*.

The chart in Fig. 2 is included here for comparison.[**]

Total Resistance

The total force (F) required to drive the vehicle at its maximum output is found by adding rolling, grade, acceleration, and wind resistances, and dividing the sum by the estimated efficiency of the power transmission system. Losses that subtract from this efficiency include gear friction, the power needed to run the alternator,

[*] The formula is given here without explanation of how it is derived, since the subject is too complex for this work and every car is different; for more information see: Motor Car Engineering, Clark, p. 84-91.
[**] The Motor Car, Duncan McMillan, London: Longmans, Green, 1915, p.6.

compressor(s)[***] , and other accessories. They do not include losses in the power plant; this will be taken up later in this chapter.

$$\boxed{F = \frac{F_R + F_G + F_A + F_W}{E}}$$

For example, if the sum of the four main resistances is 1, and the estimated efficiency is 50%, then F = 1 ÷ .50 = 2.

Torque requirement

The torque required for driving the vehicle is the total force × the wheel radius:

$$\boxed{\begin{array}{l} T = F \times r \\ F = T \div r \end{array}}$$

where:

T = torque at axle

r = wheel radius, inches.

[***] Unlike the formulas for air engine output, the formulas for compressor power consumption are quite common in textbooks; I have included at the end of this section only the charts (Figs. 3, 4, 5,and 6) built from these formulas.

Power Required to Compress Air*

Altitude, ft.	Isothermal compression					Adiabatic compression							
	Single- and two-stage					Single-stage			Two-stage				
	Psig					Psig			Psig				
	60	80	100	125	150	60	80	100	60	80	100	125	150
0	10.4	11.9	13.2	14.4	15.5	13.4	15.9	18.1	11.8	13.7	15.4	17.1	18.7
1,000	10.2	11.7	12.9	14.1	15.1	13.2	15.6	17.8	11.6	13.5	15.1	16.8	18.3
2,000	10.0	11.4	12.6	13.8	14.8	13.0	15.4	17.5	11.4	13.2	14.8	16.4	17.9
3,000	9.8	11.2	12.3	13.5	14.4	12.8	15.2	17.2	11.2	13.0	14.5	16.1	17.5
4,000	9.6	11.0	12.1	13.2	14.1	12.6	14.9	13.9	11.0	12.7	14.2	15.7	17.1
5,000	9.4	10.7	11.8	12.8	13.7	12.4	14.7	16.5	10.8	12.5	13.9	15.4	16.7
6,000	9.2	10.5	11.5	12.5	13.4	12.2	14.4	16.2	10.6	12.2	13.6	15.1	16.4
7,000	9.0	10.3	11.2	12.2	13.0	12.0	14.2	16.0	10.4	12.0	13.4	14.8	16.0
8,000	8.9	10.0	11.0	11.9	12.7	11.8	14.	15.7	10.2	11.8	13.1	14.5	15.6
9,000	8.7	9.8	10.7	11.6	12.4	11.6	13.7	15.4	10.0	11.6	12.8	14.1	15.3
10,000	8.5	9.6	10.4	11.4	12.1	11.5	13.5	15.1	9.8	11.3	12.6	13.8	15.0

Fig. 3.--Theoretical horsepower required at altitude to compress 100 cfm free air.

Altitude, ft.	Single-stage			Two-stage			
	Psig			Psig			
	60	80	100	60	80	100	125
0	16.3	19.5	22.1	14.7	17.1	19.1	21.3
1,000	16.1	19.2	21.7	14.5	16.8	18.7	20.9
2,000	15.9	18.9	21.3	14.3	16.5	18.4	20.5
3,000	15.7	18.6	20.9	14.0	16.1	18.0	20.0
4,000	15.4	18.2	20.6	13.8	15.8	17.7	19.6
5,000	15.2	17.9	20.3	13.5	15.5	17.3	19.2
6,000	15.0	17.6	20.0	13.3	15.2	17.0	18.8
7,000	14.7	17.3	19.6	13.0	14.9	16.6	18.4
8,000	14.5	17.1	19.3	12.7	14.6	16.2	18.0
9,000	14.3	16.8	18.9	12.5	14.3	15.9	17.6
10,000	14.1	16.5	18.6	12.3	14.1	15.6	17.2
12,000	13.6	15.9	17.9	11.8	13.5	15.0	16.5
14,000	13.1	15.2	17.2	11.3	12.9	14.3	15.7

Fig. 4.--Approximate brake horsepower required by air compessors, bhp/100 ft^3 free air actually delivered; will vary considerably with the size and type of compressor.

* Figs. 3, 4, and 5 are taken from Compressed Air and Gas Handbook, John P. Rollins, p. 10-92 & 10-93.

Discharge pressure			Isothermal compression, single or multistage		Adiabatic compression based on a value for *n* of 1.3947				Theoretical intercooler gauge pressure	% power saved by two-stage over one-stage adiabatic compression
					Single-stage		Two-stage			
Psig	Psia	Atm abs	Mep	Theoretical hp per 100 ft^3	Mep	Theoretical hp per 100 ft^3	Mep, psi referred to L.P. cyl	Theoretical hp per 100 ft^3		
5	19.7	1.34	4.13	1.8	4.48	1.96				
10	24.7	1.68	7.57	3.3	8.21	3.58				
15	29.7	2.02	10.31	4.5	11.4	5.0				
20	34.7	2.36	12.62	5.5	14.3	6.2				
25	39.7	2.70	14368	6.4	16.9	7.4				
30	44.7	3.04	16.30	7.1	19.2	8.4				
35	49.7	3.38	17.90	7.8	21.4	9.3				
40	54.7	3.72	19.28	8.4	23.4	10.2				
45	59.7	4.06	20.65	9.0	25.2	11.0				
50	64.7	4.40	21.80	9.5	27.0	11.8				
55	69.7	4.74	22.95	10.0	28.7	12.6				
60	74.7	5.08	23.90	10.4	30.3	13.3				
65	79.7	5.42	24.80	10.8	31.9	13.9				
70	84.7	5.76	25.70	11.2	33.3	14.6	29.2	12.8	20.6	12.3
75	89.7	6.10	26.62	11.6	34.7	15.2	30.3	13.3	21.6	12.5
80	94.7	6.44	27.52	12.0	36.0	15.7	31.3	13.7	22.7	12.7
85	99.7	6.78	28.21	12.3	37.3	16.3	32.3	14.1	23.6	13.5
90	104.7	7.12	28.93	12.6	38.6	16.9	33.2	14.5	24.5	14.2
95	109.7	7.46	29.60	12.9	39.8	17.4	34.2	14.9	25.5	14.4
100	114.7	7.80	30.30	13.2	40.9	17.9	35.0	15.3	26.3	14.5
110	124.7	8.48	31.42	13.7	43.2	18.9	36.7	16.1	28.1	14.8
120	134.7	9.16	32.60	14.2	45.2	19.8	38.3	16.8	29.8	15.1
130	144.7	9.84	33.75	14.7	47.2	20.7	39.6	17.3	31.5	16.4
140	154.7	10.52	34.67	15.1	49.2	21.5	40.8	17.9	32.9	15.7
150	164.7	11.20	35.59	15.5	51.0	22.3	42.3	18.5	34.5	17.1
160	174.7	11.88	36.30	15.8			43.6	19.0	36.1	
170	184.7	12.56	37.20	16.2			44.7	19.5	37.3	
180	194.7	13.24	38.10	16.6			45.8	20.0	38.8	
190	204.7	13.92	38.80	16.9			46.8	20.4	40.1	
200	214.7	14.60	39.50	17.2			47.8	20.9	41.4	
250	264.7	18.00	42.70	18.6			52.5	22.7	47.6	
300	314.7	21.40	45.30	19.7			56.5	24.5	53.4	
350	364.7	24.81	47.30	20.6			59.6	26.1	58.5	
400	414.7	28.21	49.20	21.4			62.7	27.4	63.3	
450	464.7	31.61	51.20	22.3			65.3	28.6	67.8	
500	514.7	35.01	52.70	22.9			67.8	29.6	71.2	
550	564.7	38.41	53.75	23.4			70.0	30.6	76.3	
600	614.7	41.81	54.85	23.9			72.3	31.3	80.5	

Fig. 5.--Theoretical horsepower required to compress air from atmospheric pressure to various pressures--mean effective pressures (mep)

Power to compress 1 cfm free air to:	Horsepower:
500 psig	.316
1000 psig	.364
1500 psig	.385
2000 psig	.400

Fig. 6
("Compressed Air for City and Suburban Traction", Herman Haupt, 1897.)

The Power Available

Notation

Selecting Engine Specifications

TABLE 1.--THEORETICAL RATIOS OF PRESSURES AND TEMPERATURES DUE TO THE EXPANSION OF COMPRESSED AIR IN AN ENGINE CYLINDER

1 Cutoff	2 Ratio of expansion = 1 ÷ cutoff	3 Ratio of mean to total absolute pressure, for entire stroke	4 Ratio of mean to total absolute pressure, during expansion only	5 Ratio of initial to final temperature	6 Ratio of initial to final absolute temperature, due to expansion only	7 Rato of inital to final absolute pressure for ratio of expansion
.10	10.00	.249	.166	.391	.513	.039
.15	6.67	.348	.233	.460	.578	.069
.20	5.00	.436	.295	.518	.627	.104
.25	4.00	.515	.353	.568	.669	.142
.30	3.33	.585	.408	.612	.705	.184
.35	2.86	.647	.460	.652	.737	.228
.40	2.50	.706	.510	.688	.767	.275
.45	2.22	.757	.558	.722	.794	.325
.50	2.00	.802	.604	.754	.818	.378
.55	1.81	.842	.649	.784	.841	.433
.60	1.67	.877	.692	.812	.862	.487
.65	1.54	.907	.734	.839	.882	.545
.70	1.43	.932	.774	.865	.902	.605
.75	1.33	.954	.814	.889	.920	.667

TABLE 2.--ACTUAL CUTOFF DUE TO CLEARANCE, FOR THE NOMINAL CUTOFFS IN COLUMN 1

Nominal cutoff	**Percentage of Clearance**						
	.03	.04	.05	.06	.07	.08	.10
.10	.126	.135	.143	.151	.159	.167	.182
.15	.175	.184	.191	.198	.206	.213	.227
.20	.223	.231	.238	.245	.252	.259	.273
.25	.272	.279	.286	.293	.299	.305	.318
.30	.320	.327	.333	.340	.346	.352	.364
.35	.368	.376	.380	.387	.392	.398	.409
.40	.417	.423	.429	.434	.439	.444	.455
.45	.465	.471	.477	.481	.486	.490	.500
.50	.514	.519	.524	.528	.533	.537	.546
.55	.564	.568	.571	.576	.580	.585	.591
.60	.612	.615	.619	.623	.626	.630	.637
.65	.660	.664	.667	.670	.673	.676	.682
.70	.709	.711	.714	.717	.720	.722	.727
.75	.758	.760	.762	.764	.766	.768	.772

P_I, intake pressure (absolute); on all but first stage, $P_L = P_R$ of previous stage

U, cutoff as a decimal fraction of 1; $U = \frac{1}{\sqrt[1.406]{\frac{P_I}{P_x}}}$. (This formula was used to construct Table 1; select cutoff from table).

U_{eff}, working cutoff taking clearance into account, stroke length + clearance length = cylinder gross length; cutoff length + clearance length/gross cylinder length = working cutoff; example: 6" cylinder with 3.14" stroke and nominal .875 cutoff, 6" - 3.14" = 2.86"; .875 × 3.14 = 2.7475"; 2.7475" + 2.86" = 5.6075"; 5.6075/6 = .9346 cutoff (effective). (This formula was used to construct Table 2).

P_m, mean effective pressure (absolute) = $P_I - P_x$, then see chart column 3

T°, final temperature (absolute), see chart column 6, beginning temperature 20° F. = 481° absolute (assumed; this is conservative, for cold winter conditions)

P_x, exhaust pressure (absolute), see chart column 7, $P_x = \frac{P_I}{\left(\frac{1}{U}\right)^{1.406}}$

P_R, pressure (absolute), after warming to 20° F. (or 481° abs.), $P_R = \frac{481}{T^\circ} \times P_x$

D, piston diameter, inches

S, piston stroke, inches

F, piston force, lbs. = $P \times A$

C, compression ratio = $\frac{P_I}{14.7}$; first stage only

P, effective gauge pressure, psig = P_m - 14.7

L, piston stroke, feet = S/12

A, piston cross-sectional area, square inches = $\left(\frac{D}{2}\right)^2 \pi$

N, rpm

K, power strokes per cylinder per cycle = 2 for double-acting cylinders, 1 for single-acting

Q_c, cfm (cubic feet per minute) compressed air consumption = ULANK/144

Q, cfm free air consumption = $Q_c \times C$

IHP, indicated horsepower (power before losses) = PLANK/33,000

E, engine efficiency including all losses, a decimal fraction of 1

BHP, brake horsepower (power after losses) = IHP $\times$ E

$\frac{\text{cfm}}{\text{bhp}}$, free air consumption per horsepower output, what you get for what you use; this is the bottom line in the economical use of air; $\frac{\text{cfm}}{\text{bhp}} = \frac{Q}{\text{BHP}}$

T_Q, torque, lb.-ft. = $\frac{\text{BHP} \times 5252}{N}$

T_A, torque, lb.-in. = $T_Q \times 12$

Torque and Horsepower Conversions: $\text{BHP} = \frac{T_A \times N}{63{,}024}$; $T_A = \frac{\text{BHP} \times 63{,}024}{N}$

Shaft Dimensions

A°, total angle of deflection in degrees = $\dfrac{583.6 \times T_A \times L_S}{D_S^4 \times E_M}$

T_A, torque, lb.-in. = $\dfrac{BHP \times 63{,}024}{N}$

L_S, shaft length, inches

E_M, modulus of elasticity of material, 12,000,000 for steel; not listed on Air Engine Design Data sheet

D_S, shaft diameter, inches

A°_{PF}, angle of deflection per foot of shaft length, maximum .08° for solid round steel shaft

$$= \frac{A^\circ}{\frac{L_S}{12}} = A^\circ \times \frac{12}{L_S} = \frac{A^\circ 12}{L_S}.$$

How to Use the Formulas

Photocopy the blank chart, "AIR ENGINE DESIGN DATA" and fill in the blanks, choosing different given factors such as pressure, piston size, rpm, number of stages, cutoff, etc. Play around with it, changing one thing at a time so you know what effect your changes will have. Low numbers for the $\frac{cfm}{bhp}$ factor should be one of your main goals. Use the cutoff charts as they have been prepared for you by true compressed air engineers. Economical use of air can be obtained by a combination of these influences: (1) low cutoff (but the exhaust gauge pressure must be positive; subtract 14.7 from absolute pressure to get gauge pressure); (2) compound (multi-stage) engine design so air is re-used in two or more cylinders; the trick is to continue using low cutoff and provide interheaters to absorb ambient heat between expansion stages; the formulas above take into account power added by ambient heat; remember that each added stage is also a drawback because of added weight and cost of valves, heat exchangers, etc; (3) use air as close as possible to maximum tank pressure; avoid anything that reduces pressure without generating power, such as regulators, tight bends, small hoses and other restrictions; if it is necessary to use air at a considerably lower pressure than storage pressure, use heat exchangers before admission to stage one piston; (4) use low speed engine, and compensate with large, long pistons; the longer the air is in the engine, the more time it will have to absorb ambient heat; fill every available space with ambient-heat-absorbing devices and try to make them out of lightweight materials; shell-and tube heat exchangers are best because the drive air doesn't have to make tight bends which cause unwanted expansion; (5) use final exhaust to drive an ejector which pulls ambient air through the tubes of the shell-and-tube heat exchanger.

In choosing a shaft, keep in mind that a given power transmitted at a lower speed has more torque, and must be larger in diameter, and shorter, to prevent twisting

(deflection). This should not influence you to try building an air engine that runs at high speeds; the air needs time to absorb ambient heat while it's in the process of expanding, and the extra wear from fast reciprocation is not desirable.

Other Factors

Other factors to take into account are gear ratios in the differential and the main gearbox (if any--expansion engines don't need reverse gearboxes if they have reversing valve motion linkages, and because they have high torque at low speed, they don't need a plurality of forward gears either; a variable cutoff is a much better way to deal with varying loads and speeds). The vehicle driveshaft torque, the torque at the wheels, and the torque put out by the engine shaft are going to be three different numbers, depending on gear ratios and wheel diameter.

Travel speed = wheel RPM × wheel circumference;
wheel RPM × 60 = wheel revolutions per hour,
wheel diameter × π = wheel circumference, inches;
circumf. inches ÷ 12 = circumf. feet,
circumf. feet ÷ 5280 =circumf. miles.

$$\text{mph} = \frac{\text{RPM} \times 60 \times \text{wheel diameter} \times \pi}{12 \times 5280},$$

$$\text{and} \quad \frac{60 \times \pi}{12 \times 5280} = .002975 = \frac{1}{336.13524}.$$

Therefore,

$$\boxed{\begin{aligned} \text{mph} &= \frac{\text{RPM} \times \text{d}}{336} \\ \text{RPM} &= \frac{336 \times \text{mph}}{\text{d}} \end{aligned}}$$

where:

d = wheel diameter in inches
mph = vehicle linear speed
RPM = wheel revolutions per minute.

A chart should be used to juggle these factors, along with engine rpm, gear ratios, ratio of axle to driveshaft speed, etc. Because of the high speed of commercial auto engines, compared to the top speed of an expansion engine (250-1000 rpm), if you're planning to build an air car from an existing vehicle, the differential ratio, etc., will have to be taken into account.

P_I													
U													
U_{eff}													
P_m													
$T°$													
P_x													
P_R													
D													
S													
F													
C													
P													
L													
A													
N													
K													
Q_c													
Q													
IHP													
E													
BHP													
$\frac{\text{cfm}}{\text{bhp}}$													
T_Q													
T_A													
$A_{PF°}$													
$A°$													
T_A													
L_S													
D_S													

Letters to the Editors of Engineering Journals

Automotive Engineering, November 1976

Compressed-Air Hybrid

Some of your readers, who studied the interesting article on Electric Vehicles in the August edition, may like to spare a passing thought on the merits of pneumatic vehicle propulsion. Almost all the arguments and relationships presented in the paper still hold good if compressed air is substituted for electricity. But the real interest lies in the differences.

It is not likely that a reasonable range can be achieved on stored compressed air alone, so that a hybrid, with an engine covering mean power demand to drive the air compressor, needs to be considered.

The potential transmission efficiency of a pneumatic transmission is high compared to the electric analogue and if heat from the charging engine exhaust is used to heat the driving air, a transmission efficiency in excess of unity is possible. In fact, with an open circuit layout, such an arrangement is necessary to avoid freezing in the air motor exhaust.

There is no limit to the charge or discharge rates and no difficulty in applying 100% regenerative braking. What is more, it is a lot simpler to store air at, say, 100 psi than to store electric energy in a high speed flywheel. There is also no battery charging loss and no battery weight; the storage weight of compressed air is small and it all but disappears if chassis members are made to double as air receivers. The weight of air motors is infinitesimal compared to electric drive motors and nothing cleverer than a few valves is needed for propulsion control. There would be two or more air motors, so there is no need for a differential either.

The charging engine, which either stops or runs at constant speed and load, can be tuned to maximum efficiency and minimum exhaust emission and if the economy steps found necessary for the electric vehicles are applied to the pneumatic hybrid, it should be possible to attain quite phenomenal fuel mileages.

Finally, the traditional skills of the automotive industry could readily encompass the development and production of such a vehicle.

Dr. S. G. Bauer, Derby, England

Mechanical Engineering, March 1983

Air Compressor-Driven Autos

To the Editor:

It's a mystery why energy conservation efforts have focused on a dead phoenix such as the electric car and the friction-plagued flywheel, while our factories use a readily storable 95 percent pollution-free energy called compressed air.

Coupling a compressor to the existing engine of an auto or truck would provide compressed air to air motors driving the vehicle wheels. The savings in energy would result from shutting the engine off in an off/on cycle whenever the pressure in a small air storage vessel was high enough to move the vehicle from stopped position such as a stop-light, and as air

demand decreases in downhill/slowing for a stop condition. With the proper air circuit design, dynamic braking would be achieved with the air motors in a compressor mode for the latter conditions.

Since the air supply could be varied to meet the road needs, the vehicle engine would operate at a constant, most economical rpm to replenish the air. I guesstimate a 10-minute supply of compressed air in the storage vessel would be able to allow the engine to restart on demand as the vehicle is moving to replenish the supply. Naturally air motor engine starting is desirable.

An existing auto could be modified with off-the-shelf compressor, air motors, valves, etc. The only design required is for adapters to attach the above components, and a special foot-operable pressure regulator which would replace the accelerator pedal.

With this arrangement no transmission is necessary.

Irving Weinberg, St. Louis, Mo.

Mem. ASME

The Burt Air Drive

Robert Burt's air car is an excellent example of a hybrid air car equipped with a closed cycle power plant. The only disadvantage of the closed cycle is that it doesn't bring in outside energy, but this could be changed by clever manipulations and additions to the cycle. The greatest virtue of the closed cycle, especially pertinent in auto power plants, is the lower size and weight of the equipment. For more information on the closed cycle, see the next chapter.

San Marino Tribune, January 3, 1980

Air Compression Moves Auto

Burt's Kit Converts Auto

Dr. Robert Burt of San Marino has an idea which could revolutionize the auto industry—a kit, installed in any auto, that would transform the engine from a gas-eater to an air-user. Burt says it's a matter of "changing a car's appetite."

Actually this isn't just an idea. It's an invention he perfected in 1932 and he has updated it and plans to utilize this "Burt Retrofit Kit" in his 1966 Cadillac. Originally he called his invention the "Burt Air Drive."

"There is more energy in one gallon of gasoline than in 20 pounds of dynamite," says Burt. That energy only moves a Cadillac 10 miles proving that gasoline is a "very inefficient energy."

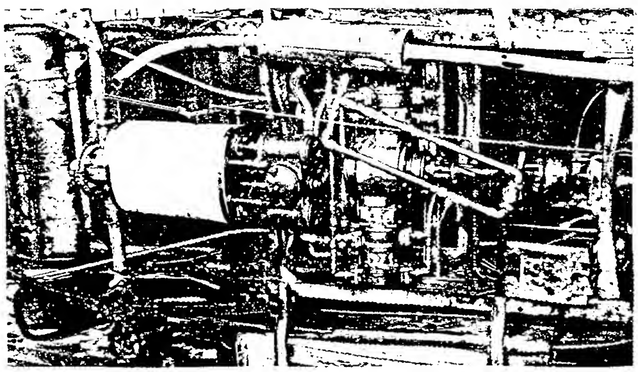
Simplified, Burt says his idea uses the steam engine technique but makes use of compressed air instead of steam.

How does it work? Burt says it's really very simple.

Its principle is the same as a locomotive except that the "works" are underneath the auto. He adds that the motor runs by taking air out of the storage area (containing about 250 psi) and pumps it up to three times that pressure.

The engine-compressor unit replaces the boiler and fire box of the steam car, and the clutch, gearbox and propeller shaft of conventional cars.

Burt says the engine is more efficient because "it is like having a 10-speed overdrive. The engine is never used to slow or stop the car; the air motors are reversed and energy is saved. What cannot be stored is by-passed through a safety valve and passed through the radiator.



Underside of Burt's 1932 Plymouth retrofitted with Stanley Steamer engine to run on air. Stanley engine at left; compressor in center.

"The air, after compression, is used to cool the engine cylinders and is also superheated in the exhaust system, therefore recovering much power from wasted heat."

The kit Burt proposes for general marketing includes a small standard four-cylinder engine which is really the prime mover and an air compressor attached to that engine. The air flows into a high pressure tank resembling a scuba bottle for storage of energy. and an air valve performs like a throttle controlling the air from the storage tank to the motor. The fire wall is directly connected to the drive shaft. Simply open the throttle and air drives the motor that moves the car, he says.

It will work easily in any auto because various kits will be designed to fit and bolt onto the existing auto frame. i.e., a certain numbered kit will fit uniformly all autos of a certain size. There will be kits to fit onto all autos, he says.

The reason why Burt knows his ides is usable is because in 1932 he converted a Plymouth and it ran. Then his idea echoed back to him in 1973 when gas lines started forming.

Burt says, "If we could cut gasoline consumption by 75%, we would also cut the pollution by that percentage. I think we can cut it (consumption) by 95%."

But Burt doesn't reserve his talents to improving only the auto. He is the inventor of the photo-electric cell which he describes as "the radio tube that receives light and controls electric current by the action of light." He also has a patent on the first cathode ray oscilloscope and the bone-conduction hearing aid later taken over by commercial organizations. Another of his developments was the Beltone talking picture theater equipment. While serving at Lockheed he a won a $100 war bond-for the best production shortcut invention of the month—anti-glare welders' goggles which he designed in collaboration with the Corning Glass Works.

Burt has always been a natural when it comes to inventions. At the age of 10 he had already started a business as "doorbell doctor" in his home town, Battle Creek. Michigan. He often ended up fixing other electric gadgets in the homes he visited and soon invented a glider which had everything present-day models have except towing devices to get it into the air.

After graduating from Cornell University in 1921, he continued his studies and received his Ph.D. in physics from Caltech. Failing to get into WW II because of an injury

due to an auto accident, he did research work for General Electric and Western Electric, before getting his degree at Caltech.

Let's hope that in about 18 months—Burt's prediction for manufacture of the auto kit—all of us will be able to buy the Burt Retrofit Kit and transform all our cars into air-users instead of gas-guzzlers.

U. S. Patent No. 2,120,546, *Mechanical Transmission,* *Patented* ***June 14, 1938 by*** *Robert Cady Burt of Pasadena, California*

This invention relates to apparatus for the transmission and control of mechanical energy, force, power, or effect, from a source to any desired point.

This invention has for its object the transmission of mechanical power with great flexibility of power and speed and fine control.

This transmission of power is accomplished through the medium of an elastic gas, vapor or fluid.

In the following disclosure and claims the term "fluid" is used broadly to denote gas, vapor, air, or compressible liquid, or other material of like characteristics.

A compressor or pump is attached to the source of power and this compressor takes the fluid at a pressure P_1 and compresses it to a higher pressure P_2 thus doing mechanical work on the fluid and storing in the fluid the energy of compression.

Another mechanism, known as a motor, takes this fluid and expands it back from pressure P_2 to P_1 thus extracting the power stored in the fluid during compression.

For many uses of this transmission it is desirable to use compressed air for the working substance or elastic fluid, and in many places in this disclosure I shall refer to the elastic fluid as the air, but I do not limit my invention to a transmission using air. In fact, under certain conditions other vapors appear to be more desirable.

Referring to the drawings: Fig. 1 is a sectional view of an air compressor; Fig. 2 is a pressure volume diagram of an air compressor; Fig. 3 is a graph showing the variation in work done by an air compressor when the initial volume and final pressure are held constant and the initial pressure is varied; Fig. 4 illustrates one specific application of this transmission to a motor car; Fig. 5 is a diagram of the high pressure control system; Fig. 6 is a diagram of the low pressure control system; Fig. 7 Is a horizontal longitudinal sectional view of the air motor.

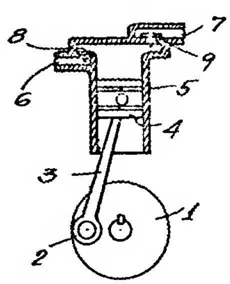


Fig 1.

In Fig. 1 is diagrammed an ordinary air compressor. having a crankshaft **1**, a crank **2**, connecting rod **3**, piston **4**, which moves up and down with the rotation of the crankshaft inside of the cylinder **5** which the piston tightly fits. On the down stroke of the piston air is drawn into the cylinder through the intake **6** and inlet valve **8** and is compressed on the up stroke of the piston, being forced out of the compressor through check valve **9** and exhaust outlet 7. The amount of compression depends upon the intake pressure P_1 and the pressure into which the exhaust is discharging or P_2.

It is well known to engineers that the work performed by the piston on the gas in this operation is equal to the integral of the pressure multiplied by elemental changes in volume taken around the cycle.

To illustrate:—assume we have a cylinder of 100 cubic inches capacity, that it is filled with air at 15 psi and that no air can escape until we have compressed this air to a pressure of 750 psi. Curve 10 of Fig. 2 shows how the pressure within this cylinder increases as the volume is decreased until 750 psi pressure is reached and then the air is exhausted. The statement in the preceding paragraph simply states that the work done by the cylinder on the air is proportional to the area to the left and below the curve 10 and above the horizontal line of 15 psi and to the right of the vertical line representing zero volume.

In the formulae employed to explain my invention the following characters appear and have the meanings here set forth:

P_1 = pressure of fluid prior to compression.
P_2 = pressure of fluid after compression.
P or p = pressure of a fluid, generally.
V or v = volume of a fluid, generally.
T = temperature of a fluid, generally.
K = gas constant of a fluid, generally.
C_p = specific heat of a fluid at constant pressure.
C_v = specific heat of a fluid at constant volume.
W = work of compression of a fluid.
e = the logarithmic exponent = 2.718.
K^1 = a constant related to K.
V_1 = volume of fluid prior to compression.
γ = C_p divided by C_v.

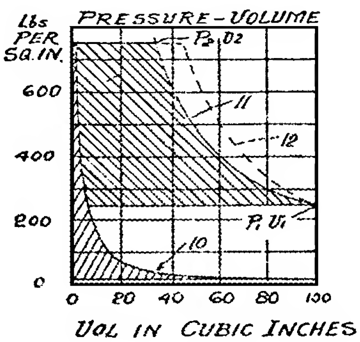


Fig. 2.

If the compression has been performed isothermally or at constant temperature, the equation of the curve is given by Equation 1, as follows:

$$PV \equiv KT \tag{1}$$

If the compression has taken place adiabatically or without loss of any heat by the air, then the equation is that given by Equation 2, as follows:

$$PV^{\gamma} = \text{Constant} \tag{2}$$

Curve 11, Fig. 2 represents the same equation (No. 1 above) as curve 10, except that the initial pressure P_1 is higher and the work done is represented by area bounded by the lines P_1 = 250 psi; v = zero; P_2 = 750 psi; and the curve 11. Curve 12 represents the Equation 2 above, at the same volume and pressure as curve 11.

$$\frac{C_p}{C_v} = \gamma \tag{3}$$

Equation 3 states the well known gas law:--specific heat at constant pressure C_p, divided by specific heat at constant volume C_v, is a constant. This constant is represented by the Greek letter γ. For air it is 1.4.

To obtain the expression for the work of compression at constant temperature, we proceed as follows:

$$\text{Work}\left(\text{T constant}\right) = \text{W} = \int \text{pdv}$$

Or, instead of integrating *pdv* around the cycle, we may integrate *vdp* between the limits of P_1 and P_2, which is the same thing. Thus,

$$W = \int_{P_1}^{P_2} vdp = P_1V_1\int_{P_1}^{P_2} \frac{dp}{p} = P_1V_1\left[\log_e p\right]_{P_1}^{P_2} = P_1V_1\log_e\left(\frac{P_2}{P_1}\right) \tag{4}$$

The expression for the work of adiabatic compression is derived as follows:

$$PV^{\gamma} = K, \text{ or } P^{\frac{1}{\gamma}}V = K^1$$

$$W = \int_{P_1}^{P_2} vdp = P_1^{\frac{1}{\gamma}}V_1\int_{P_1}^{P_2}\frac{dp}{P^{\frac{1}{\gamma}}}$$

$$= \frac{P_1^{\frac{1}{\gamma}}V_1}{1-\frac{1}{\gamma}}\left(P_2^{-\frac{1}{\gamma}} - P_1^{1-\frac{1}{\gamma}}\right)$$

(5)

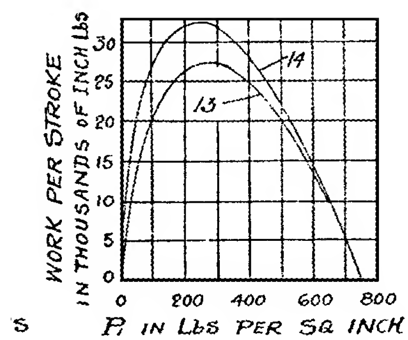


Fig 3.

If the initial volume V_1 and final pressure P_2 are held constant, and if different values of the input pressure P_1 are taken, it will be found that the work done by the compressor increases as P_1 increases up to a certain value and then decreases as P_1 approaches P_2 in value. This is shown graphically as an example in Fig. 3: here V_1 is taken as 100 cu. inches; P_2 is taken as 750 psi; and the work W is plotted against the different values of P_1. Curve 13, Fig. 3 corresponds to Equation 4 and curve 14 corresponds to Equation 5. Both curves have maxima at nearly the same value of compression ratio. These maxima are obtained by differentiation of Equations 4 and 5, obtaining 6 and 7 below.

Differentiating Equation 4, holding P_2 constant, we have

$$P_1V_1\log_e\left(\frac{P_2}{P_1}\right) = P_1V_1\left(\log_e P_2 - \log_e P_1\right)$$

$$\frac{dW}{dP_1} = \left(\log_e P_2 - \log_e P_1\right)V_1 - \frac{P_1V_1}{P_1} = \left(\log_e\frac{P_2}{P_1} - 1\right)V_1$$

Equating the derivative

$$\frac{dW}{dP_1}$$

to zero to find the maximum value for W, results in a maximum value appearing when

$$\frac{P_2}{P_1} = e = 2.718 \tag{6}$$

Differentiating Equation 5, holding P_2 constant, we have:

$$W = \frac{P_1^{\frac{1}{\gamma}} V_1}{1-\frac{1}{\gamma}}\left(P_2^{1-\frac{1}{\gamma}} - P_1^{1-\frac{1}{\gamma}}\right) = \frac{V_1}{1-\frac{1}{\gamma}}\left(P_1^{\frac{1}{\gamma}} P_2^{1-\frac{1}{\gamma}} - P_1\right)$$

$$\frac{dW}{dP_1} = \left(\frac{V_1}{1-\frac{1}{\gamma}}\right)\left(P_2^{1-\frac{1}{\gamma}} \frac{P_1^{\frac{1}{\gamma}-1}}{\gamma} - 1\right)$$

By equating to zero, we find a maximum value for W when

$$\frac{P_2}{P_1} = \gamma^{\frac{\gamma}{\gamma-1}} \tag{7}$$

For air, $\gamma = 1.4$, and

$$\frac{P_2}{P_1}$$

becomes 3.2 for maximum work.

It is also evident from Fig. 3 that much more work can be obtained from a given cylinder working at a limited upper pressure P_2 by proper selection of the initial pressure P_1. For example, the compressor diagrammed in Fig. 2 would absorb less than 6000 inch lbs. per stroke when operating from atmospheric pressure to 750 psi as in curve 10 and it would absorb more than 27,000 inch lbs. per stroke when operating from 250 psi to the same upper pressure.

From the foregoing consideration, it is evident that a power transmission can be designed using previously compressed air for its low pressure intake and compressing it over a comparatively small pressure ratio to a higher pressure. Then, after transmission through a pipe and control, the compressed air can be expanded through an air motor back to the same pressure as that from which it started.

By this means a transmission of extreme lightness, flexibility, compactness and economy and having other desirable features, may be obtained.

Fig. 4 shows a specific application of this transmission to a motor car and, while I do not limit my invention to automobile transmissions, it will serve as an example to illustrate the principles involved.

Referring to Fig. 4, **31** is a gasoline engine having a radiator **32**, carburetor **33**, and exhaust manifold **34**. This engine, being started in any of the usual manners, drives a small auxiliary compressor **35**.

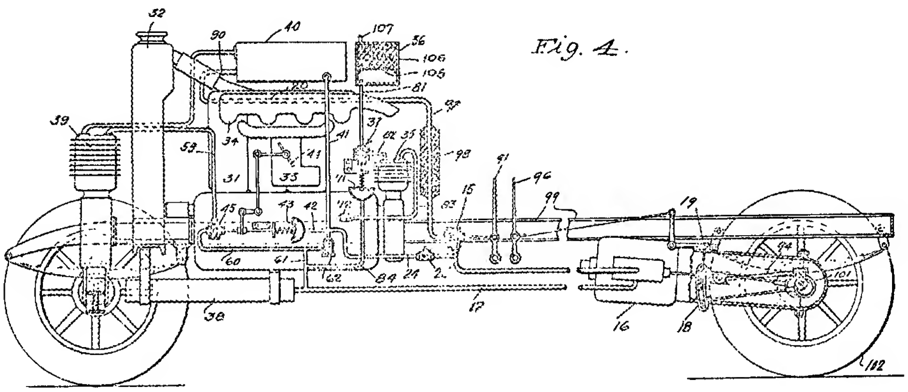
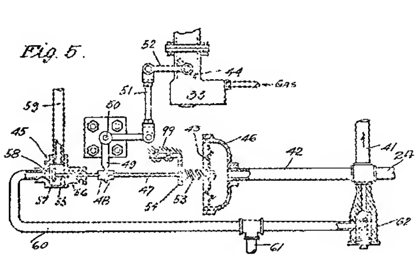


Fig. 4.

This compressor takes air from the atmosphere through a cleaner, conventionally illustrated at **36**, and throttle **37**, compresses and discharges it through the pipe shown into tank **38**. The cleaner **36** may consist of a box or can having supported, spaced from the bottom a wire screen **105** above which is placed bronze wool **106**. The intake pipe **107**, open to the atmosphere, enters at the top, and the discharge pipe **81** passes out the bottom of the cleaner. At the same time the power compressor **39** has been taking air from **38**, compressing and discharging it into tank **40**. This process is continued until the pressure in tank **40** has been built up to a certain predetermined value, for example, 750 psi. When P_2, the pressure to tank **40**, has reached this pressure the connecting tube **41** and the tube **42** transmit this pressure to the diaphragm **43** which expands closing the throttle **44** of carburetor **33** and closing the intake to pump **39** by action of valve **45**.

The action of this control mechanism can be best understood by referring to Fig. 5. Diaphragm **43** is secured at its outer edge to shell **46** which is mounted on the car frame **99**. Attached to the center of diaphragm **43** is a rod **47** on which are nuts **48** spaced somewhat apart. Carried between these nuts is bell crank **49** pivoted about a center **50** and operating on the butterfly valve **44** of carburetor **33** through links **51** and **52**. The movement of diaphragm **43** due to pressure in shell **46** is resisted by springs **53** which is in compression between the diaphragm and bracket **54** mounted on the car frame. An extension **55** of rod **47** passes through packing **56** and carries a cone **57** that seats against seat **58** of valve **45** when diaphragm **43** is extended. Compressor **39** takes in air through pipe **59**, valve **45**, pipe **60**, pipe **61**, from the low pressure tank **38**. It is obvious, then, that the action of the diaphragm **43** under pressure is to close the engine throttle **44** and also the valve **45**, choking off the intake to the compressor and unloading it.

Fig. 5.

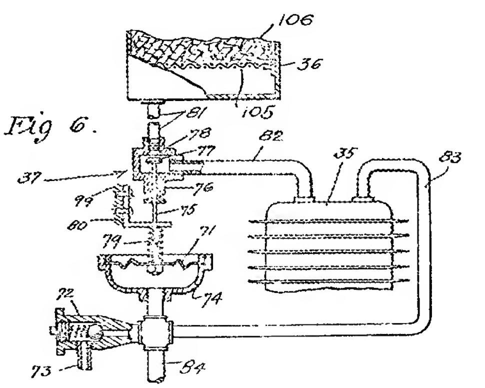


At this stage the engine idles under little or no load and the pressures are maintained. When P_1 reaches its proper value, for example, 350 psi, then diaphragm **71** closes valve **37** and no more air is pumped into the system until some escapes. Should pressure P_1 become too high, safety valve **72** lets air escape to atmosphere through pipe **73**. In the same manner safety valve **62**, allows air to escape from tank **40** through pipes **41**, **60**, and **61** back to low pressure tank **38**, if P_2 should become too high.

The action of the low pressure control can be seen in detail by referring to Fig. 6. Diaphragm **71** is secured at its outer edge to shell **74** which is mounted on the car frame.

Attached to the center of the diaphragm is rod **75** that extends through packing **76** and carries a cone **77** that seats on valve seat **78** of valve **37** when diaphragm **71** is extended. The movement of the diaphragm is resisted by spring **79** which is in compression between diaphragm **71** and bracket **80** mounted on the car frame. Compressor **35** takes air from the atmosphere through cleaner **36**, pipe **81**, valve **37**, and pipe **82**, discharging it through pipe **83**, and pipes **84** and **61** into low pressure tank **38**. When the pressure in tank **38** reaches a predetermined value the diaphragm **71** will have extended, pushing the rod **75** upward and closing the valve **37**. The compressor **35** is then unloaded and inactive until the pressure in tank **38** drops sufficiently to permit the diaphragm actuated valve to open and allow air to be taken in by the compressor.

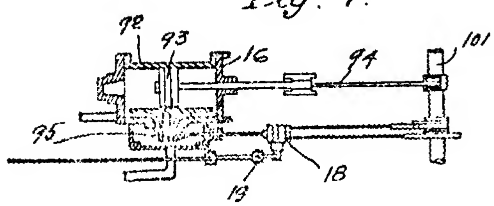
Fig. 6.



High pressure air from tank **40** is brought back through pipe **90**, through throttle valve **15**, operated by lever **91**, to the intake side of engine **16** which expands the air and returns it to tank **38** through pipe **17**. Thus no air is lost from the system.

Engine **16** is exactly like a steam or compressed air engine having the usual cylinder **92**, piston **93**, connecting rod **94**, and valve mechanism **18** which through the valve link **19** controls the time of cutoff and admission as well as the exhaust events through change of the phase relation of valve **95** with respect to piston **93**. A standard Stephenson link has been shown and since this valve gear is so old and so well known to those skilled in the art, it is not considered necessary to explain its operation in detail. The connecting rod **94** operates through a crank to turn rear axle **101** to which are attached driving wheels **102**.

Fig. 7.



The entire mechanism up to throttle **15** and return pipe **17** is automatic; the entire control of the automobile is accomplished by manipulation of the throttle **15** through lever **91** and control **19** through lever **96**. These are operated exactly in the same manner as a steam engine.

Many economies may be incorporated in this system. For example: compressor **39** and tank **38** may be placed out in front where, being in the air stream incident to the travel of the vehicle, they would be cooled, thus reducing the volume of air to be compressed, and the compressor **39** and tank **38** are so shown in this preferred arrangement in Fig. 4. The high pressure air may be passed through a heat interchanger **20** in the exhaust manifold for the purpose of expanding the air, or reducing its density, by taking waste heat from the exhaust gases. The pipe **97** and engine **16** may be heat insulated to conserve this heat.

Another economy of the system is that the gasoline engine is always working under high torque and never running at high speed and light load. As will be understood from the control operations explained, the engine is always either operating with full compressor load, or is idling at closed throttle with the compressor unloaded.

A simple pipe **24** and check valve **25** shunting valve **15** permits regenerative braking. For regenerative braking the valve **15** is closed and the links **19** are gradually shifted to the reverse position, thus causing air to be taken from tank **38**, compressed by engine **16** and driven through pipe **24**, check valve **25** and pipe **41** back into tank **40**. This continues until a higher pressure is reached in tank **40**, of, perhaps 1200 psi. Thereafter air escapes through relief valve **62** into tank **38** again with a small amount of heating, due to the Thompson-Joule effect.

After this regenerative braking process, the excess pressure is available for subsequent acceleration without any call upon the motor **31**.

1200 B.H.P. Diesel-Compressed Air Locomotive for the German State Railways

One article on these engines states that they provided a fuel savings of 26% over the straight Diesel locomotives in use at the time. For a photo see the chapter on history.

(excerpts from The Engineer, May 2, 1930:)

At the time the locomotive was ordered, the following position influenced the builders and the railway officials in their decision to adopt compressed air transmission. Up to the time of the placing of the order experience had already been gained with internal combustion locomotives embodying the direct drive, the geared drive, the fluid transmission drive, and the electric drive, while locomotives embodying these different systems had either been built and tested or were then in course of construction. At that time, however, a locomotive of the internal combustion type operating with compressed air transmission had not been built. On many sides the opinion prevailed that such a method of power transmission was valuable on several grounds. Thus, the hyperbolic curve of tractive power for compressed air working approached very closely that for steam and fitted in well....

On the other hand, there were those who foresaw difficulties, and did not hesitate to prophesy failure. It was said that the efficiency of the compressed air system of power transmission was lower than that of any other system, and it was also suggested that explosions arising from oil in the compressed air might take place, while stoppages could occur owing to the formation of ice on the cylinders in which the air was to be expanded.

Such statements were made even after actual experience with the locomotive showed that such happenings did not occur. We are informed that, in fact, the efficiency of transmission with the oil-compressed air system has been demonstrated to be higher than with the oil-electric system, enabling a 12 per cent. saving on the fuel used per ton-kilometre to be recorded at a common speed of 60 kiloms. per hour. There have been no explosions of oily vapour, even although in a works test it was sought to produce such explosion artificially by the introduction of electric sparks.

During the long series of trials which have been carried out, there was at no time any signs of ice formation on the cylinders of the locomotive. On the contrary, when the hand was placed in the air at the exhaust outlet it was quickly withdrawn, since the air, after being expanded to close upon atmospheric pressure, still retained a temperature of about 100° Cent. No difficulties have been experienced with the deposit of dirt from particles of lubricating oil or carbon in the air reheater, or with the clogging of the air compressor valves from like causes....

In the following table the general particulars of the locomotive and the leading dimensions of the oil engine and air compressor are given....

Locomotive Particulars.

Type	4—6—4
Tractive effort at driving wheel rims	12,000 kilos.
Diameter of driving wheels	1600 mm.
Diameter of locomotive cylinders	700 mm.
Stroke of locomotive cylinders	700 mm.
Adhesive weight	54,600 kilos.
Weight empty	118,600 kilos.
Weight in working order	124,000 kilos.
Maximum designed speed	80 kilom. per hr.

Oil Engine and Air Compressor Particulars.

Type of engine	M.A.N.four-stroke single-acting
Number of cylinders	Six
Bore of cylinders	450 mm.

	Continuous load.	Short overload.
Designed B.H.P. output	1000	1200
Designed I.H.P. output	1350	1630
Revolutions per minute	400	450

Working air pressure:	6.5 atm. (92.3 psi) to 7 atm. (99.4 psi)
Temperature of air at locomotive cylinders:	330 ° to 360° Cent.
Type of air compressor:	Twin-cylinder single-stage double-acting
Diameter of cylinders	640 mm.
Stroke	350 mm.

...The compressed air on leaving the compressor passes directly to a reheater, which operates on the contra-flow principle, and by utilising the heat of the exhaust gases raises the temperature of the air to 360° Cent. From the reheater the air passes through the regulator control valve to the two cylinders of the locomotive in which it is expanded to practically atmospheric pressure.

Chapter 7: Closed-Cycle Pneumatic Power Plants

For an excellent technical discussion of an air car design using a closed-cycle, see the section on Robert Burt in the chapter on hybrid pneumatic power plants

Return-Pipe Compressed Air Practice

(Frank Richards, Power, February 16, 1915)

A letter from a California correspondent asks why it is that more has not been made of the Cummings system of compressed-air power transmission. He says that from the results which have been actually attained by the system it could be advantageously employed in many places, especially as, besides the economy of it, there is no danger of fire or explosion, and it can be operated under water.

Notwithstanding that the return-air or two-pipe pumping system, for raising water by the direct pressure of air, is quite extensively and successfully employed in different parts of the country, and that this system has been fully described in various publications, the essential principles of the Cummings system in its entirety are not generally well understood even where it happens to be known at all. Patented a full generation ago, it seems to have been exploited mostly in California, and it may be worthwhile to call the attention of power users to it again.

It is rather curious that the new departure which this system represents—the use of higher pressures—is quite in line with the improvements in steam engines, in oil engines, especially of the Diesel type, and in electrical practice. It may be claimed, however, that the two-pipe air system "goes them one better." In the compound or the triple-expansion steam engine it seems to be the last added portion of the pressure which secures the economy, but the entire range of the pressure from the bottom to the top has all been retained, while the compressed-air system here to be spoken of retains and uses only the higher, and presumably more profitable, range of pressure.

The essential feature of the system is the constant maintenance of a high pressure upon the air employed. Instead of continually compressing fresh atmospheric air up to, say 100 lb. gage, using it in the motor at that pressure, with or without expansion, and then exhausting the air into the atmosphere again, a constant intake pressure of, say 100 lb. is maintained at the compressor. The air is compressed to, say 200 lb., is transmitted to and is used in the motor at that pressure, and then is exhausted and carried back to the compressor at a pressure of 100 lb., to be compressed and used again, and so on.

DIFFERENT PRESSURE RANGES COMPARED

The accompanying diagrams, Figs. 1, 2, 3, are all drawn to the same scale for equitable comparison, and may be studied together, although each represents an operation entirely distinct from and unrelated to the others; that is, they are not successive stages of one operation. In each case the same volume of air fills the cylinder at the beginning of the compression, but the actual weights or quantities of air are very different, only Fig. 1 beginning the compression with "free air," or air at atmosphere pressure.

Fig. 1 represents the adiabatic compression of a given volume of air from atmospheric pressure, say 15 lb. to the inch absolute, to a gage pressure of 100 lb., or 115 lb. absolute. Fig. 2 shows the compression of an equal volume (not an equal weight) of air,

but under an initial pressure of 100 lb. gage, to a delivery pressure of 200 lb.; and in Fig. 3 an equal volume of air at 200 lb. is compressed to 300 1b.

In each case the initial volume of air compressed is represented by the area of the rectangle ABDCA. When the air has been compressed to the gage pressure specified in each ease its volume is represented by the area EBDFE, and this will be the volume assumed to be discharged into the pipes and receiver. As we are speaking now from the purely theoretical viewpoint, nothing is said about clearance or other allowances made in practice.

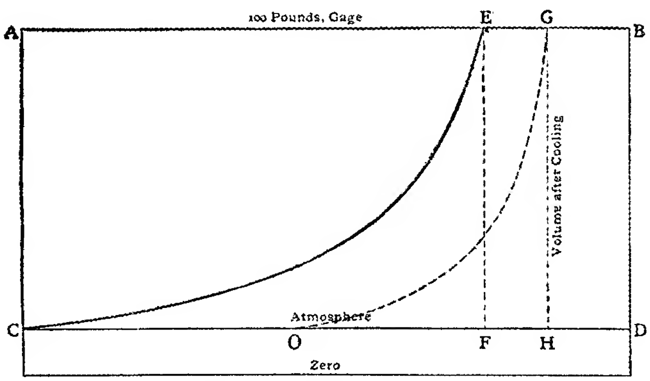


Fig. 1.—Air between 0 and 100 psig.

It is well understood that the operation of compression invariably increases the temperature of the air very much, but this temperature it is impossible to maintain, and unless reheating is employed, the air is never used at the high temperature at which it is delivered by the compressor. As the air cools to normal temperature before it is used, its volume being reduced proportionately, the actual volume available for use is represented by the area GBDHG, this being in Fig. 1 only about an eighth of the initial volume, and not much more than one-half the volume EBDFE, as delivered by the compressor.

The air delivered under either compression represented may be said to have equal working value, volume for volume, the available pressure being 100 lb. in either case, the air in Fig 1 at 100 lb. working against atmosphere only, the air in Fig. 2 at 200 lb. working against a back pressure in the return pipe of 100 lb., and that in Fig. 3 at 300 having a back pressure of 200 lb.

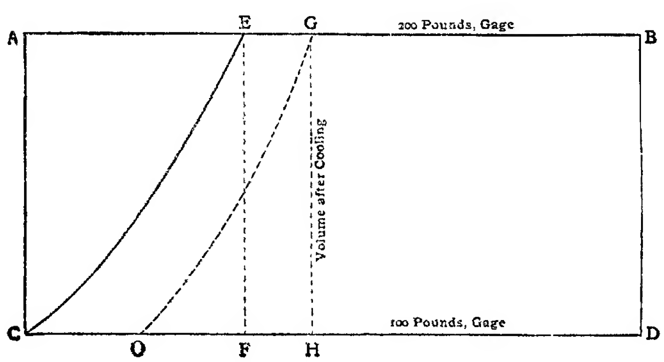


Fig. 2.—Air between 100 and 200 psig.

In compressing air from 100 to 200 lb., as in Fig. 2, the temperature of the air is not raised nearly as much as in Fig. 1 and, consequently, the shrinkage in cooling from volume EBDFE to volume GBDHG is proportionately much less than in Fig. 1. The volume GBDHG here available for work is more than one-half the initial volume ABDCA, or four times the volume available in Fig. 1. At the same time it is be noted that the mean effective pressure in the compressor cylinder for the stroke, which is the measure of the actual work of compression, is decidedly less than double that of Fig. 1. Getting fully four times the available volume for less than double the power employed certainly looks like doubling the efficiency by halving the relative cost of the compression.

In Fig. 3, compressing the air from 200 to 300 lb., the heating of the air is still less and the consequent shrinkage by cooling also is less. The available volume delivered, GBDFG, is five times the corresponding volume in Fig. 1, while the mean effective pressure required for the compression and delivery of the air is less than 2.1 times as much, which seems to be decidedly more than doubling the efficiency.

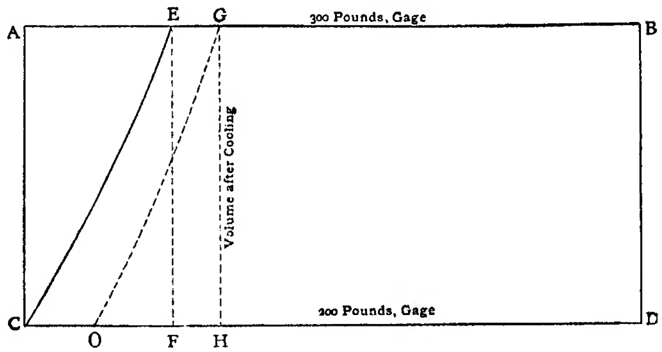


Fig. 3.—Air between 200 and 300 psig.

It has been assumed in each case above that the initial air temperature is 60 deg. F. With the same increase of 100 lb. in pressure the final temperatures will be 485, 163 and 121 deg., the rise of temperature being respectively 425, 103 and 61 deg. The enormous rise of temperature in compressing from atmospheric pressure has led to the general adoption of two-stage compression, with intercooling of the air thereby gaining something in economy, avoiding the overheating of the surfaces, the burning of the lubricants and the danger of fires and explosions. With the heating that occurs in Figs. 2 and 3 there is no necessity for employing the two-stage compressor, and little possibility of any increased economy through its employment.

The ratio of final and initial absolute pressures is: In Fig. 1, 7.666; in Fig. 2, 1.869; in Fig 3, 1.465. The ratio of the volume after cooling to 60 deg., or the volume available for use, to the initial volume is: in Fig 1, 0.1304; in Fig. 2, 0.535 and in Fig. 3, 0.6825. The relative costs of compression, as measured by the power used, or the mean effective pressures for the compression divided by the volume after cooling are: In Fig. 1, 11.6 ÷ 0.1304 = 319; in Fig. 2, 78.88 ÷ 0.535 = 147; and in Fig. 3, 86.83 ÷ 0.6825 = 127. Here the ratio of the cost in Fig. 1 is 319 ÷ 147 = 2.17, and of Fig. 1 to Fig. 3 it is 319 ÷ 127 = 251.

It is understood that wherever this air is used—that is, the air of Fig. 2 and Fig. 3—whether for driving a rock drill, for a steam pump or an air motor of any kind, the air instead of being discharged into the atmosphere, as it would be from Fig 1, is piped back to the compressor with only 100 lb. of its pressure used; then, volume for volume, the air used would be of the same power value in either case, if not used expansively. As the available volume delivered as shown in Fig. 2 is four times that in Fig. 1, a compressor of one-fourth the capacity, or, at equal piston speeds, with a cylinder one-half the diameter, will be sufficient for the work. The maximum unbalanced pressure against the piston would be no greater in one case than in the other, only it would be continued for a longer or a shorter portion of the stroke. There would be no additional strength required in any of the working parts of the machine, except that the air cylinder and connections would have to be strong enough for the maximum pressure.

As the same air is used over and over again in the two-pipe system, arrangements being provided for making up leakage losses, there is no appreciable accumulation of moisture and no possibility of freezing up even if sufficiently low temperatures should

occur, which they do not. At the same time more or less of the lubricant is carried back and forth in the air and comes in contact with the working surfaces. As the system is a closed one, being entirely out of touch with the surrounding atmosphere and not affected by the local pressure, it will work at one altitude just as well as at another.

WHY THE SYSTEM'S USE HAS BEEN LIMITED

Now as to why the system has not been more extensively employed; there is the fact to begin with that even yet it is not generally as well known and understood as it should be. Then, evidently, it would not be likely to be much used for intermittent work, such as the driving of rock drills, which are continually changing their location, and where the maintenance of the return connection would cost in time and trouble enough to cancel the prospective advantage.

Apparently the best employment of the system would be for the driving of ordinary steam pumps where constant pressure is usually required for practically the entire stroke. The air of Fig. 2 at 200 lb. pressure and 100 lb. back pressure, or the air at the higher pressures of Fig. 3 does not permit much profitable expansion in use. When used for rotative purposes in an engine or motor, the cutoff, as the compression diagram suggests, should never occur earlier than three-quarter stroke, so that the cutoff that may be accomplished by a good slide-valve engine would be all that would be available in any case. In this respect the air in Fig 1 would have some advantage, as, to secure the greatest economy, it should be cut off before half-stroke, and a certain saving would be accomplished by the expansion which would not be possible where the higher pressure were employed.

There is a necessity for the compressor supplying the air and the engine or motor using the air to approximately keep pace with each other, not necessarily stroke for stroke but so that, with the aid of suitable receiver capacity, the delivery and the return air pressures shall be maintained as constant as possible. This implies that the two working units of the system should be adapted to each other in capacity and that an automatic pressure governor should control the compressor.

U. S. Patent No. 456,941, Apparatus for Transmitting Power by means of Compressed Air, Patented Aug. 4, 1891, by Charles Cummings of Oakland, California.

(excerpted and paraphrased by the editor)

Object of invention: to provide better, cheaper, more compact, and more efficient means for transmitting power by compressed air, whereby the best results may be achieved in applying energy to work at a remote location from where the power is generated, with the least possible loss in transmission.

Comprising: the use of two unequal pressures, both above atmospheric, and kept at a contant ratio to each other, the air circulating through a system of pipes and other parts that is closed to the atmosphere. The confined body of air is alternately expanded and compressed; the air used is not drawn from the atmosphere or exhausted thereinto once the system has been charged, except for supplying the slight loss due to leakage. A prime mover drives the air compressor, which creates two unequal pressures, for example, 100 and 200 psig. There is a system of pipes provided with valves; the pipes carry the air

to the driven apparatus, where the compressed air is to do its work. The air circulates constantly between the compressor and the motor, passing through reservoirs and receivers, if desired. In the air driven motor apparatus, the unequal air pressures will be on opposite sides of the piston, leaving the piston unbalanced and permitting it to move in the ordinary way. Hence in one part of this circulating system the air is at one pressure, while in another part it is at another pressure, the air being subject to constant change from one pressure to another as it circulates. This change takes place alternately; the air, when at high pressure, does its work in the motor and then exhausts into the low pressure air and so continuing until it again reaches the compressor and is reconverted into high pressure air. This change of volume takes place with little loss of power through heat, promoting efficiency.

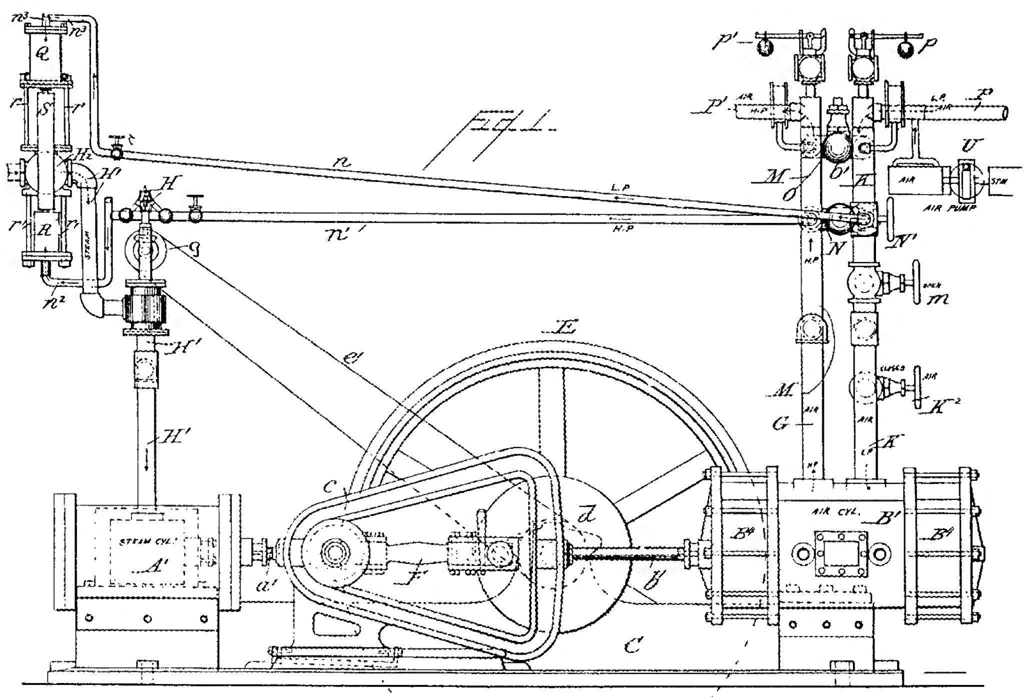


Fig. 1.—Side elevation.

Lettered Components, All Drawings:

A A', the steam cylinders; any prime mover could be used that is suitable for driving the compressor; the steam cylinders are in line with the compressor cylinders for convenience

a a' b b', piston rods

B B', the two parallel cylinders of the air compressor (Figs 4, 5, 6, 7)

B^2 B^2, compressor pistons

B^3, bore of the cylinder in which the compressor piston operates

B^4 B^4, hollow heads bolted to each end of the compressor cylinders (Fig.6)

C, main frame or bed of the machine

c c, yokes between rods of steam pistons and compressor pistons, firmly connected thereto

D, main shaft

D' D', bearings carrying main shaft in frame

d d, crank-disks at each end of main shaft, with crank pins set at right angles so that the engine may start when the connecting-rods are in any position
E, band-wheel
E', governor pulley
e e, eccentrics
e', belt passing around the governor pulley and the pulley *g* on the shaft of the ball-governor
F F, connecting-rods, pivoted at one end to the crank-pins, and at the other end to points within the yokes
f f, eccentric rods, connected to the valve rods

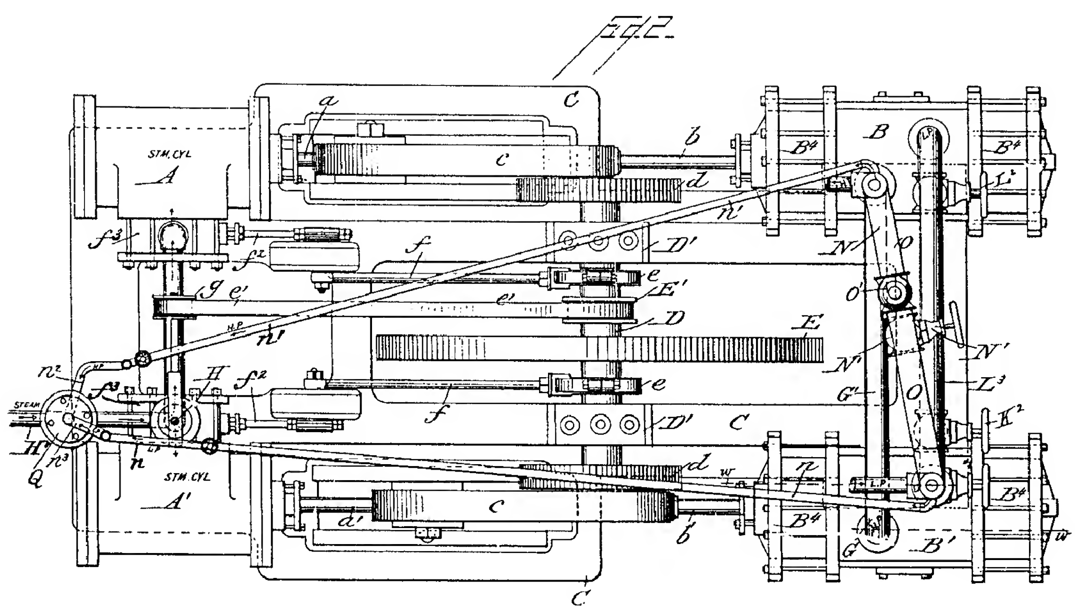


Fig. 2.—Top plan view.

$f^2 f^2$, valve rods
$f^3 f^3$, valve chests on the sides of the steam cylinders
G, vertical pipe entering the upper side of the compressor cylinder *B'* and receiving air from the channel *J'*, in conjuction with which it forms the high pressure compartment of the cylinder (Figs. 3.and 4)
G', horizontal pipe connecting pipes *G* and *M*, since the latter have the same function
H, ball-governor (see Figs. 1 & 2) serves the useal purpose by controlling a valve in the steam pipe; adjusted to prevent accidents in case anything happens to the air governor
H', steam pipe from the boiler to the steam cylinders, passing through the air governor valve chamber H^2 (as shown in Fig. 1)
H^2, hollow valve chamber between governor cylinders *Q* and *R*
h, water jacket surrounding bore of compressor cylinder
h' h' heads of compressor cylinder bores, constituting the inner vertical walls of the hollow heads B^4, of which they are an integral part; each has four openings (Fig.5), two of which lie on one side of the partition *I*, and two on the other

H^3, air governor valve in steam pipe H', of any suitable construction; graduates flow of steam through the steam-pipe from the boiler to the engine in proportion to the amount of work to be done; see below description, "Operation of the Air Driven Motor Apparatus"

I, vertical partition dividing compressor cylinder head into two compartments (Fig.5)

i, valve casing screwed horizontally into the head *h'*

i' i', a suitable number of openings in the casings *i* of the discharge valves; the casing of the suction valves don't have these openings, but are open at the end

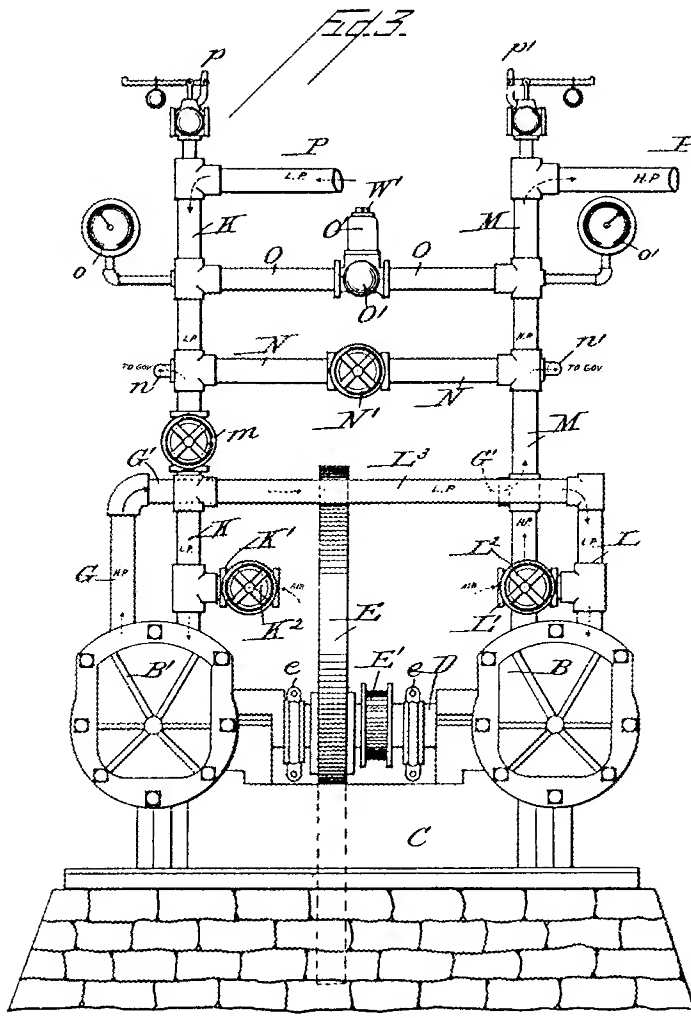


Fig. 3.—Right-hand end elevation.

i^2, coiled spring surrounding the casting *j*, tensioned between the flange on nut *j'* and the diaphragm which supports the casting in position, to keep the valve normally closed

J J', horizontal channels in the main body of the cylinder, above the water jacket, divided by a longitudinal partition exactly in line with the partions *I I* in each head; in conjunction with the chambers in the heads, and in communication therewith, these channels form two separate longitudinal compartments, and connect the two head chambers

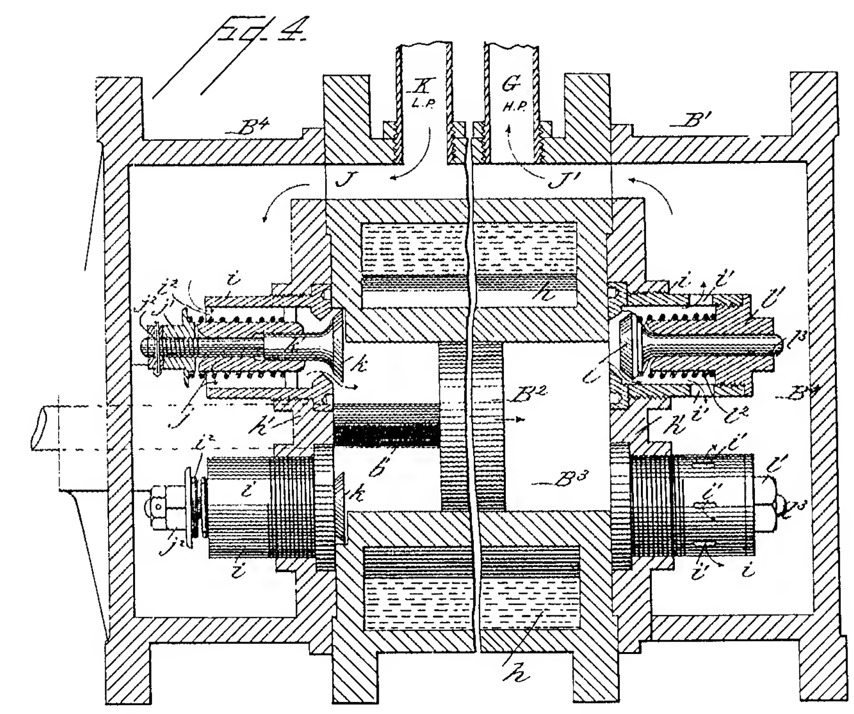


Fig. 4.—Enlarged longitudinal section on line *w w* of Fig. 2.

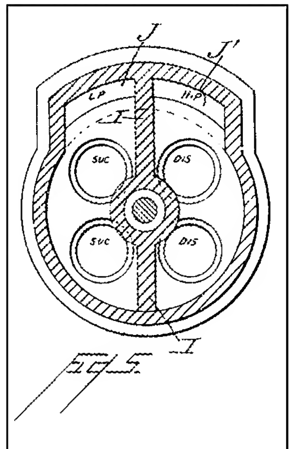


Fig. 5.—Cross-section on line *z z* of Fig. 6.

j, stationary tubular casting in the suction valves (Fig. 4, at left) supported by a vertical perforated diaphragm within the valve casing so as to leave an annular space btwn the casting and the casing

j', flanged nut on the outer end of suction valve stem

j^2, jam nut or collar secured with a pin on the outer end of suction valve stem

K, vertical pipe entering the upper side of the compressor cylinder *B'* and discharging into the channel *J*, in conjuction with which it forms the low pressure compartment of the cylinder (Figs. 3.and 4); when valve K^2 is open, it serves as a conduit for atmosphere; when valve *m* is open, it serves as a conduit for the lower of the two unequal pressures; the main low pressure pipe, extending vertically for some distance, as far as necessary

K', short horizontal branch of pipe *K*, opening into the atmosphere

K^2, valve on pipe *K'*; open when apparatus is being charged

k, suction valve, with inclined seat and adapted to open inwardly into the bore

k', suction valve stem horizontal within the tubular casting

L L' L^2, serving for compressor cylinder *B* the same function that *K K'* K^2 serve for cylinder *B'*

L^3, horizontal pipe connecting pipes *L* and *K*, since the latter have the same function

l, discharge valve

l', casting within the perforated casing *i* of the discharge valve, leaving an annular space; enlarged at the outer end and screwed into the outer end of the valve casing

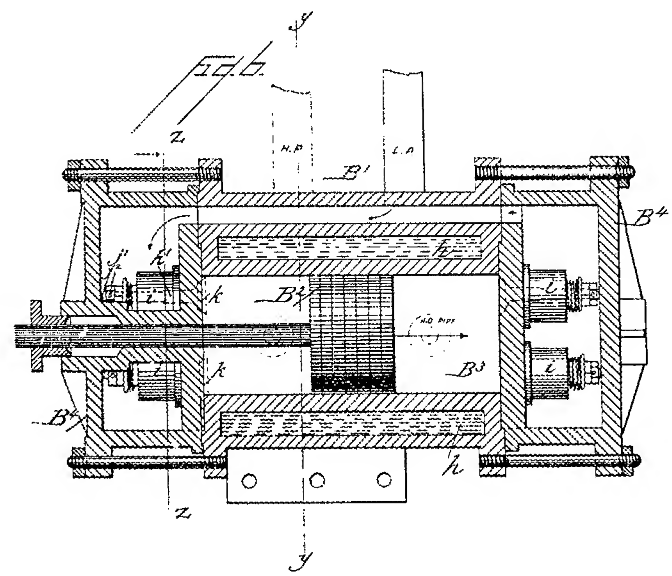


Fig. 6.—Longitudinal section on line *x x* of Fig. 7.

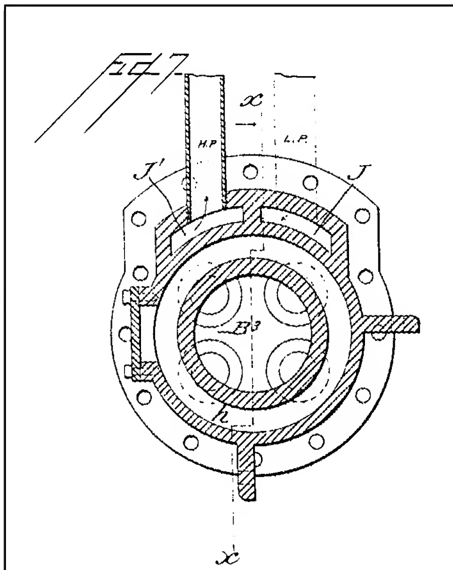


Fig. 7.—Cross-section on the line *y y* of Fig. 6.

l^2, spring coiled around the casting *l'*, bearing at one end against the valve and at the other end against a shoulder on the casting, and holding the valve in a normally closed position

l^3, discharge valve stem horizontal within the casting *l'*, with a beveled seat and opening outwardly from the bore

M, serving for compressor cylinder *B* the same function that *G* serves for cylinder *B'*; the main high pressure pipe, extending vertically for some distance, as far as necessary

m, valve closed when the valve K^2 is open to charge the system

N, horizontal pipe connecting main high and low pressure pipes *M* and *K* (Fig.3)

N', manual valve in pipe *N*

n n', two pipes leading from opposite ends of pipe *N* to the air governor, where pipe *N* joins low pressure pipe *K*, and at its other end high pressure pipe *M* (Figs. 1, 2, 3)

n^2, bent pipe connected to the lower end of high pressure governor cylinder R, through which oil is fed into the cylinder when needed; its upper end is higher than cylinder *R*

n^3, pipe projecting from the upper end of low pressure governor cylinder Q, through which oil is fed into the cylinder when needed

O, horizontal pipe connecting main high and low pressure pipes *M* and *K* (Fig.3), at a point above pipe *N*; used only at certain times, see below

O', automatic valve in pipe *O*

o, pressure gauge in pipe *K*

o', pressure gauge in pipe *M*

P, pipe connected to the upper end of low pressure pipe *K*, receiving exhaust from the motor or the driven apparatus where the power is applied to the work

P', pipe connected to the upper end of high pressure pipe *M*, delivering air to the motor or the driven apparatus where the power is applied to the work

p, safety valve in pipe *K*

p', safety valve in pipe *M*

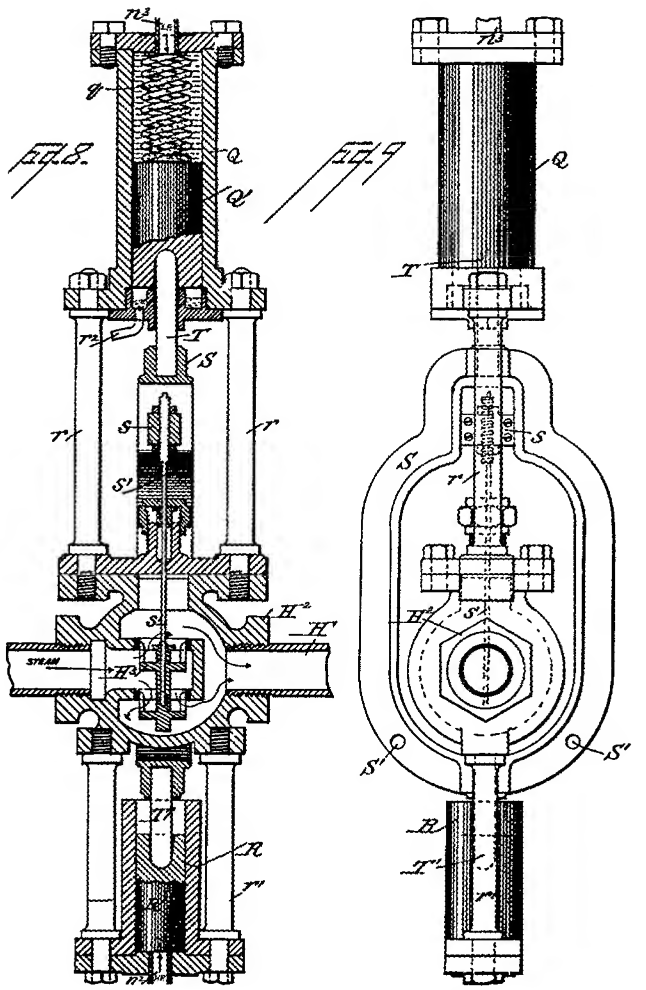


Fig. 8.—Vertical section of the air governor device.

Fig. 9.—Side elevation of the air governor device.

Q, low pressure governor cylinder, a vertical cylinder at the upper end of air governor where low pressure pipe *n* is connected; filled above piston *Q'* with oil or some lubricant

Q', trunk piston of a certain area, in cylinder *Q*

q, spring in low pressure governor cylinder, immersed in the oil therein; it allows the governor valve H^3 to open and close gradually, cushioning its movements

R, high pressure governor cylinder, a vertical cylinder at the lower end of air governor where high pressure pipe *n'* is connected; filled below piston *R'* with oil or some lubricant

R', trunk piston in cylinder *R*, of a certain area less than the area of piston *Q'*

r r, vertical bolts which secure governor valve chamber to cylinder *Q* through flanges on each; they are long enough to leave a convenient space between valve chamber and cylinder

r' r', vertical bolts which secure governor valve chamber to cylinder *R* through flanges on each; they are long enough to leave a convenient space between valve chamber and cylinder

r^2, oil-drip pipe at lower end of cylinder Q, to receive any oil that may lead between piston and cylinder

S, yoke of generally oval shape, loosely surrounding valve chamber H^2, its upper end near the bottom of governor cylinder Q, and its lower end near the top of governor cylinder R

s, cross-connection near upper end of yoke *S,* with a nut that holds valve rod *s'*

s', threaded valve rod carries valve H^3 at its lower end within steam-pipe *H'*

T, short bar or rod; its upper end loosely enters a socket in the lower end of piston *Q'*, passing through the bottom of cylinder Q, while its lower end enters loosely a socket in the top end of yoke *S*; it is held in place by the downward pressure of the piston *Q'*

T', rod received loosely at its upper end by a socket at the bottom end of yoke *S*, while its lower end loosely enters a socket in the piston *R'*, the upward pressure of which holds it in place

U, small leakage supply compressor

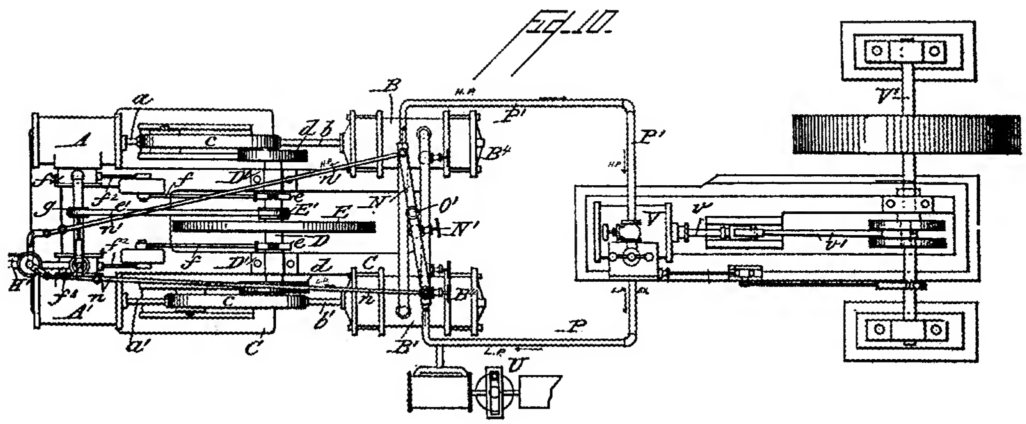


Fig. 10.—Plan view of apparatus on a diminished scale, with example of driven machinery.

V, air engine cylinder, connected to high and low pressure pipes *P* and *P'*

V', driving shaft

v, piston rod

v', connecting rod

W, threaded valve rod, projecting through the top of the casing and formed for the attachment thereto of a wrench whereby the rod and the nut W^2 may be moved up or down

W^2, nut on valve rod *W*, tongued to slide in grooves in the side of the valve casing

W^3, beveled collar forming a seat at the upper end of the casing where the rod passes through, providing an air-tight joint

w, automatic valve used during charging of system

w', spring surrounding rod *W* and bearing at one end on nut W^2 and on the other end on the valve *w*

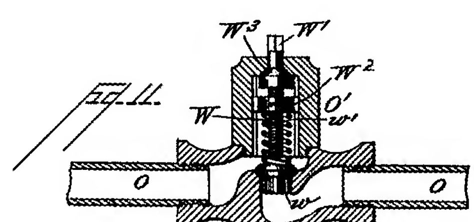


Fig. 11.—Vertical section of the automatic valve sometimes used.

Construction Details of the Compressor:

At each of the four openings in each of the heads or walls *h'*, a valve is arranged (Fig. 5). The hollow heads B^4 are large enough to hold the valve mechanisms, four at each end of the cylinder bore. A pair of suction valves are on one side of partition *I*, thus between one of the longitudinal compartments and the cylinder bore, and a pair of discharge valves are on the opposite side of the partition, thus between the other longitudinal compartment and

the cylinder bore. Each end of the compressor cylinder bore has four valves: two suction and two discharge, the suction and discharge compartments on each end created and isolated from each other by a partition. Air enters the cylinder through the open end of the suction valve, as shown by the arrows (Fig. 4.).

Pipes *K* and *M* are the main low and high pressure pipes, and extend vertically for some distance, as far as necessary.

Operation of the Air Governor:

In order to govern the two unequal air pressures, keeping them regular and constant and maintaining a fixed ratio to each other, an "air governor" is used. This governor has two functions: first, to regulate the speed of the compressor with relation to the work to be done by the driven machine—that is, to proportion the speed of the compressor so that any amount of work may be done that is required (within the machine's capacity)—and second, to maintain the desired ratio between the pressures in the circulating pipes. Construction details of the air governor are shown in Figs. 8 & 9.

Fig. 10 shows a plan view of the entire apparatus, including a plan view of one form of the driven machine (air motor).

Pipes *n* and *n'*, which communicate low and high pressure air to the governor, enter the governor by way of pipes n^3 and n^2, the oil feed pipes; therefore the air is actually acting on the surfaces of the oil in the governor cylinders, and thereby indirectly acting on the pistons.

The governor's function is not to maintain a uniform speed under all circumstances, as is the case with the ordinary steam-engine govervor, but to automatically vary the speed of the compressor to suit the work being done by the driven machine. This is done by varying the speed of the prime mover, in this case the steam engine, although the apparatus could be modified for other prime movers instead of steam.

If at any time the compressor runs faster than it needs to, the pressure in the high pressure pipe will increase and that in the low pressure pipe will decrease, and the variation of pressures influences the air governor to lessen the speed of the compressor

and restore the normal ratio of pressures. But if the compressor is running slower than it must in order to compress air as fast as the driven device(s) require, the pressure in the high pressure pipe will decrease and that in the low pressure increase; this variation of the ratio will act on the air governor and tend to increase the speed of the compressor and restore the normal ratio of pressures.

The areas of the two pistons *Q'* and *R'* have the same ratio as the two unequal air pressures; if the high pressure air is 200 psi and the low pressure air is 100 psi, the area of piston *Q'* will be twice the area of piston *R'*, since the pressure upon one inch of surface of piston *R'* will be balanced by the pressure upon two inches of surface *Q'*. In this case, therefore, when the pressure in pipe *n* is 100 psi and the pressure in pipe *n'* is 200 psi, these pressures will exactly balance each other in the governor and the pistons and other parts will remain in equilibrium. When the governor is in this condition, the parts may be adjusted up or down by hand and (except for the spring *q*) would remain in any position where they might be placed. The spring *q*, however, is interposed above the piston *Q'*, so as to add a little excess of pressure to that end of the governor and disturb what would otherwise be an equilibrium sufficiently to keep the valve H^3 normally open, although the

spring *q* is of slight power and readily overcome by any slight increase in the high pressure air. The spring is further advantageous in allowing a gentle motion in the parts of the governor. It cushions the end of the piston and prevents the shock which might take place when a change of ratio suddenly occurs and disturbs the equilibrium. The present configuration of governor is described simply as an example. This is especially true with respect to the areas of the piston *Q'* and *R'*. These areas vary in different governors where ratios between the air pressures other than two to one are used.

In order to change the ratio of pressures without altering the pistons, weights may be hung on the yoke *S* at the perforations *S'*.

Operation of the Main Apparatus:

Referring to Figs. 2 and 3, I will first describe the operation when cross-pipe *N*, having valve *N'*, is used and cross-pipe *O* is idle or is removed from the apparatus. First, the valves K^2 and L^2 will be opened to admit atmospheric pressure air in to the pipe *L'* and *K'* and from there into the compessing cylinders. The valve *N'* will also be opened manually, and the valve *m* closed. Then the compressor will be set to work, and air will be drawn from the atmosphere into the compressing cylinders, compressed therein, and sent through the pipes G M N K above valve *m* and pipes *P* and *P'*. The compressed air in the entire system will now be at the same pressure. The operation of compressing will be continued until both gauges register, say, 100 psi, supposing this to be the amount of the lower of the two unequal pressures. Then the operator will close valve *N'*. This will separate the system of low pressure pipes from the system of high pressure pipes, leaving the pressure in the former system fixed permanently at 100 psi. The operation of the compressor will continue until the air in the high pressure pipes has reached a pressure of 200 psi, when the inlet valves K^2 and L^2 will be closed by hand, preventing the admission of any more air, and the valve *m* will be opened by hand, letting 100 psi air into the compressor cylinders. We now have our closed system, wherein the air circulates between the compressor and the motor. Here, then, are the two unequal pressures of air, the ratio of the pressures being as two to one, this ratio kept constant by means of the air governor. The governor is found in practice to do its work so well that hardly any fluctuation of the ratio is perceptible on the gauges. No atmospheric pressure air is drawn into the machine during its operation. The compressor always works upon air at 100 psi instead of upon air at atmospheric pressure. To supply any leakage that may take place, I provide a little air pump *U*, (see Fig. 1,) which may be of any suitable and ordinary construction and which delivers into the low pressure pipes at some suitable point.

I will now describe the operation when the cross pipe *O*, having the automatic valve *O'*, is used. In this case the pipe *N* serves no necessary purpose, although the valve *N'* might be left open until all the pipes are filled with air at 100 psi, but is idle with the valve *N'* closed. Also the air governor is not used; instead the valves in the air pipes *n* and *n'*, running to the governor (Fig. 1), are closed. In starting the apparatus, valves K^2 and L^2 will be open; valves *m* and *O'* will be closed. Valve *O'* operates automatically, opening only when the pressure on one side of it is 100 psi greater than the pressure on the other side. It can be adjusted for other pressures.

The detailed construction of the automatic valve *O'* is shown in section in Fig. 11. The adjustment of the nut W^2 adjusts the tension of the spring holding the valve, closed so it will open at any desired pressure.

As the operation of compression proceeds, the high pressure pipes will be filled with air at 100 psi before any air will enter the low pressure pipes. As soon as the pressure against the sides of valve *O'* attains 100 psi the valve will open and let air into the low pressure pipes. As the compression continues, the air in the low pressure pipes will finally stand at 100 psi and the air in the high pressure pipes at 200 psi. The compression may continue beyond this, but probably won't. Then the valves K^2 and L^2 will be closed and the valve *m* opened, and so we again have our closed system of pipes, within which the air circulates constantly, one gauge standing at 100 psi and the other at 200 psi when the ratio is one to two. This automatic valve arrangement is used only in certain cases, mainly when the compressor is driven by a belt from a motor shaft which actuates other machinery that must be driven with a uniform motion, and so the motor shaft cannot have its speed varied; therefore an air governor cannot be used, and the automatic valve serves the purpose and keeps the difference of the pressures constant. This arrangement with pipe *O*, having valve *O'*, accomplishes a different result from that accomplished by the air governor, in that, while the air governor keeps the *ratio* of the two unequal air pressures constant, the automatically operating valve serves simply to keep the *difference* of the pressures constant. The automatic valve serves to regulate the arithmetical ratio of the two pressures, while the air governor serves to keep the geometrical ratio of the two pressures constant. This is an important difference when we come to look at the result that is accomplished.. Although this automatic arrangement with pipe *O* is generally used with belt machines and not in connection with the manual arrangement described first, it may be used in connection with the manual arrangement if the air governor should become disabled.

Among the benefits of my machine for transmitting power by means of compressed air is that it's much smaller and more compact, and therefore cheaper, easier to transport, and very much lighter in weight than the machines now used for doing a similar amount of work. This statement is easily proven by a simple calculation. Suppose it is desired to provide a cubic foot of 100 psig air at one stroke of the piston. Obviously if air at atmospheric or 15 psia is to be compressed to this required pressure, the original volume of atmospheric air will be about 7 ft^3—that is, seven times the volume of the required volume at 100 psig. But if air at 50 psig is to be compressed to the pressure of 100 psig, only 2 ft^3 of the former will be required to make one of the latter.

In the ordinary air compressor air is received into the machine at atmospheric pressure, so the cylinder must hold 7 ft^3, so that the atmospheric air can be compressed to a cubic foot of 100 psig in one piston stroke. Suppose it is desired to work the ordinary air compressor with 100 psig. In order that it may do this, air must be compressed to 115 psia, so that there may be 15 psia, or atmospheric pressure, on the other side of it.

In my apparatus after it is charged, the air is delivered to the compressor at 100 psig. Therefore if it is desired to obtain a cubic foot of air having 200 psig, which in my machine will give an unbalanced pressure of 100 psi to work with, the cylinder needs to contain only 2 ft^3 of 100 psi air. Hence where a cylinder in my apparatus requires a cubical contents of 2 ft^3 the cylinder in the ordinary compressor apparatus requires a cubical contents of 7 or 8 ft^3 in order to effect the same compression at one stroke. This shows the essential difference in respect of size between the two machines, this difference owing to the fact that in one case the compressor operates on atmospheric pressure air,

while in my compressor it acts on air already having a high pressure, and this therefore demonstates the value of my invention in making a small compact machine which is found in practice to have less than half the weight of certain other popular machines doing similar work.

Another advantage arising directly from my invention is an increase in efficiency. This may be proven by another simple calculation, as follows: When a volume of air is compressed to one-half, a certain amount of the energy gernerated is lost through the heating of the air and the consequent dissipation of energy in the form of heat. When a volume of air is compressed to one-third, a certain greater amount of power is lost through heat. When, therefore, a volume of air is compressed to one-seventh, as is the case when atmospheric pressure air is converted into air having a pressure of 115 psia to the square inch, so as to give an unbalanced pressure of 100 psi, a very much greater amount of power is lost through the dissipation of heat energy than is the case when the air is compressed to half its volume, as in my machine, where air at 100 psi is compressed to 200 psi, so as to give the same unbalanced pressure of 100 psi. Therefore it will be seen that I lose very little power from heat, and hence increase the efficiency of the machine very greatly. It is found in practice, which also confirms theoretical calculations on the subject, that a very much greater percent of the power generated at one end of the machine is applied to the work at the other end of my machine than is the case in any other with which I am familiar.

Patents on Closed-Cycle Pneumatic Power Plants

Patent	Date Granted	Patentee	Title of Patent
456,941	August 4, 1891	Chas. Cummings	Apparatus for Trans-mitting Power by means of Compressed Air (see above)
767,027	August 9, 1904	M. C. Wilkinson	Air Compression & Utilizing Device
1,017,835	February 20, 1912	M. C. Wilkinson	Apparatus for Com-pressing & Distri-buting Air Under Pressure
1,829,261	October 27, 1931	R. E. Bruckner	Power Transmitting Mechanism
2,049,078	July 28, 1936	R. M. Otis	Fluid Transmission
2,120,546	June 14, 1938	R. C. Burt	Mechanical Transmission (see earlier chapter)
2,486,982	November 1, 1949	A. M. Rossman	Pneumatic Power Unit
2,966,776	January 3, 1961	Yoshikazu Taga	Pneumatic Power Transmission System

Chapter 8: What's Possible, What's Not, and Why

When it comes to evaluating the feasibility of any proposed machine that is supposed to work without consuming fuel, the first duty of the devil's advocate is to ask, "What is the power source of this machine?"

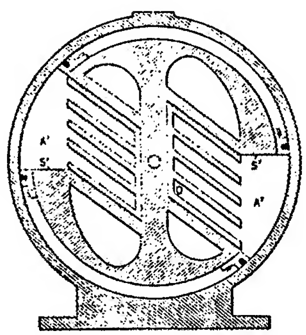
Let's apply the question to different machines, and find out where the magic comes from in each case.

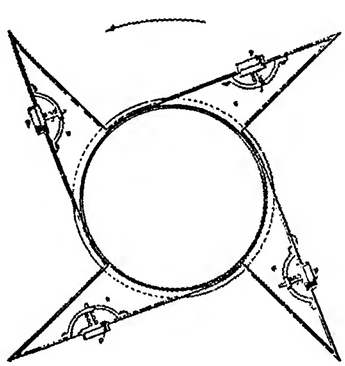
The windmill is powered by the wind. The wind is caused by warmer air masses expanding into colder air masses. These temperature differentials are caused by the solar radiation that bombards our planet 24 hours a day.

The water turbine and the ram pump are powered by flowing water. This flow is caused by gravity, which influences anything that flows to flow downhill. Then how does the water get to the top of the hill to begin with? It gets there by evaporating under the sun's rays; as water vapor it floats up through the air and falls as precipitation on the higher elevations.

The photovoltaic cell generates power by absorbing light and converting it into electricity. The light comes from the sun.

The heat pump runs on electricity, but the electrical power it consumes in order to heat the house is less than the energy it pumps into the house as heat. Where is the extra energy coming from? It's the ambient heat in the atmosphere, which is put there by the sun.





Above: Compressed air perpetual motion machines range from the patently stupid to deceptively simple yet well-engineered items like this one. Compressed air (or other elastic fluid) is contained in the chambers *A1* and *A2*. Because the surfaces *S1* and *S2* are larger than the others, the reaction on these is supposed to produce a rotary motion. No air is exhausted but should any escape past the seals, the motor also drives pumps to replenish the air pressure.

Below: Dating from 1902, this motor was claimed to depend upon a revised statement of the First and Second Laws of Thermodynamics and to consist of a special cycle of working in which the heat rejected in the Carnot cycle was interrupted and made to return to source so making it possible to convert into motive power the diffused heat at ordinary temperatures that exists in the atmosphere or elsewhere. The vessels *b*, *c*, *d* and *e* are mounted on a shaft *a*, and have one side *f* tangential to the shaft, and the other side radial. Compressed air is forced into each vessel through the valves *p*. It is stated that 'under the action of the internal pressure of the vessels, and after a slight impulse is given to same, in the direction of the arrow, the whole apparatus will begin to move and continue to do so without ever stopping, the velocity corresponding to the pressure established within the vessels.' (Perpetual Motion, the History of an Obsession, Arthur W. J. G. Ord-Hume, New York: St. Martin's, 1977.)

It seems that there is no form of "fuelless" power generator or energy mover that operates without an energy source, and those listed above are all powered by the sun, either directly or ultimately. The First and Second Laws of Thermodynamics explain what can and cannot be done in this respect. The First Law is very simple: *Energy can't be created or destroyed.* Perpetual motion machines of the first kind are impossible because they have no energy source; anything that supposedly creates its own energy source can't work.

The Second Law of Thermodynamics has been stated in many ways. As a simple, all-encompassing generality that never fails to be true—which is what a natural law should be—it is best stated as such: *In a closed system, energy transforms itself by dissipating, not by concentrating itself; therefore, the same energy cannot be re-used over and over in the same way.* A perpetual motion machine of the second kind can't work because it is an attempt to re-use the same energy over and over.

There are those who will try to state that my claims about compressed air being a form of solar energy are false, that my theory represents a perpetual motion machine of the second kind. But the self-fueling air engine is not any kind of perpetual motion machine, and here are three things that the detractors have missed, based on the three parts of the above definition of the Second Law:

1) The ambient heat that powers the self-fueling air engine is the same source of energy that powers the windmill and that provides the source of heat for the heat pump to pump. The self-fueling air engine is dependent on the atmosphere of the earth as its energy source, and the atmosphere is continuously heated by the sun. Therefore, we are talking about a perpetual energy source, not a perpetual motion machine, because the ambient medium *is not a closed system*.

2) To state that ambient heat can never provide a source of power is to play God; and as all humans who play God must someday discover, natural law will always prevail in the end over the narrowness of our little minds. It is the duty of anyone who states that ambient energy is too dissipated to use, to ask themselves, "Dissipated in relation to what?" Anyone who believes that ambient air only contains totally dissipated energy, should be able to suggest an easy, convenient way to cool a container of air to absolute zero (-460° F.), or to achieve and maintain a perfect vacuum. Or perhaps such a person would enjoy a casual trip to his friendly neighborhood tornado, cyclone, or hurricane? Surely no big deal, if atmospheric heat contains no energy to speak of.

Compressed air normally sits in the tank and cools to ambient temperature before being used. That the "little" heat it contains is still capable of doing any work at all is proof enough that the term "dissipated" must be qualified as a relative term: *How* dissipated? Dissipated *in relation to what?* My point is that *ambient heat cannot automatically be dismissed as being dissipated to the point of uselessness.*

3) If you were to set a heat pump in an airtight, well insulated shed instead of in your backyard, it would not pump heat very long. If you were to set up a windmill in your barn, instead of in a field, it would not turn. If the self-fueling air engine was expected to operate in a closed, insulated room without bringing in any outside air, it would just cool its surroundings for awhile, then quit. The self-fueling air engine doesn't recycle the same energy over and over again; its source of energy is continuous because of the large relative

size of the container from which it extracts its energy: the earth's atmosphere. *The self-fueling air engine doesn't recycle energy any more than the sun does.*

Having addressed the three components of the Second Law Of Thermodynamics one at a time and found that none of the three points applies to the self-fueling air engine, I've come to the conclusion that the self-fueling air engine neither "breaks" nor "gets around" the Law; the Second Law isn't relevant to this issue, because *what we want to do with compressed air doesn't challenge the Second Law in any way.*

> There is nothing abnormal to an efficiency greater than 1, when reheating is used; this will occur (regardless of pipe and other friction) whenever the temperature of reheating is higher than the temperature of compression.
>
> —A. E. Chodzko, Modern Machinery, January 1899

> The potential transmission efficiency of a pneumatic transmission is high compared to the electric analogue and if heat from the charging engine exhaust is used to heat the driving air, a transmission efficiency in excess of unity is possible.
>
> —Dr. S. G. Bauer, Automotive Engineering, November 1976

> They weren't perpetual motion machines, but they acted like it.
>
> —George Heaton, Builder of Air Cars, October 31, 1980

Chapter 9: Self-Fueling Claimants

The List

1920, Bill Truitt[1, 2]
1925, Louis C Kiser
1926, Lee Barton Williams
1931, Roy J. Meyers
1934, Johannes Wardenier
1934, Bob Neal[1, 2]
1949, George Heaton[1, 2]
1955, George A Gillen
1964, Constantinos Vlachos
1966, Carl Manganaro
1968, William W. Toy
1970, Ralph E. La Pointe
1970, Hudspeth & Lunsford[2]
1971, Eber H. Van Valkinburgh
1972, Russell R. Brown
197?, Samuel David Todd
1973, Garnet J. Simington
1974, John E. Holleyman
1974, Sanders Ford, Jr.
1976, Joseph P. Troyan
1976, Jaime Rios Santos
1976, John R. Murphy
1976, Harry Charles Stricklin
1977, William Long
1978, George C. Yeh
1978, Billy G. Cook
1978, John W. Rilett
1978, Baruch & Isaac Leibow[2]
197?, Des Hill
1979, Leroy K. Rogers, Sr.[2]
1980, Carl Leissler
1984, George Miller
1987, Ricardo Perez Pomar

[1] for more info see later this chapter
[2] for more info see the chapter on acoustic power

Interview with George Heaton
October 31, 1980

Toward the end of my first year of air car research, my co-worker Maria invited me to Halloween dinner with her family at their home. She said her husband, George, had built some air cars, and suggested I talk to him about his experience. I couldn't believe that someone else had thought of running cars on air. My elation at finding a possible source for usable information made up for my disappointment at not being the first.

Before dinner, Maria told me that her husband would choose his own time to bring up the topic. Some time later, George told me he'd take me aside after he'd had a little more time to think. When he finally beckoned me to join him in another room, I was paying attention. Though I wondered if this might be a prank or a misunderstanding, he hadn't been talking long before I had my notebook out.

And there was no reason to think that either Maria or her husband was a prankster. I knew from spending long hours with Maria at the shop where we both worked that she was an intelligent, conservative working mother and the wife of a friendly and generous man of many accomplishments. As he began to reminisce, George was telling me that in 1969 he'd been the vice-president of the California Fuel Dealers Association. In that role, he'd testified before a legislative committee concerning the environmental dangers involved in the use of the catalytic converters used with unleaded gas. He also warned me about compressor explosions, saying that one drop of oil contamination in an oxygen compressor could blow up a whole building. Unlike oxygen, compressed air isn't

explosive, but he wanted to impress me with the seriousness of taking safety precautions when working with pressure equipment. (Under the right circumstances, an air compressor cylinder fouled with oil can explode, like a Diesel-cycle combustion.)

George told me that around 1949, he and a friend converted some motorcycles and cars to run on compressed air. They converted the existing gas engines to run on air, with several modifications that George described.

The author at home of air car builder George Heaton, Halloween 1980

The cars they built "worked like perpetual motion machines." His wording seemed to imply that the car seldom or never ran out of air, that this is considered impossible by those who should know, that it obviously is not impossible because George has done it, and that it's still considered impossible by those who should know. The key to doing the impossible was to put low pressure air into a high pressure tank, without having to compress the air first; that is, without having to force it in against the resistance of the pressure in the tank. This allowed the use of small air pumps running off the car's motion to keep the tank full, while the engine ran off compressed air leaving the other end of the tank. George didn't remember exactly how to get low pressure air into a high pressure tank, but he thought a good compressor man could probably figure it out. He did recall that the air entered the tank in a stream of quick spurts, or pulses, and he thought it might have entered the tank "at an angle or something."

The carburetor was removed and a brass plate bolted over the gasoline intake hole. The air was injected through the spark plug holes. In an alternate configuration, the original intake ports were used, and the a 2-cycle camshaft replaced the original 4-cycle camshaft. The pipes from the air pumps were fitted with fins made from sheet metal and soldered to the pipes, to help cool the air. Separate tanks were used for storage and for driving.

George and his friend "weren't engineers enough to know what pressures to use," and he thought that it might have been because of this they had trouble with their engines blowing. That didn't keep them from driving their air cars across the country several times. The last time George was driving his air car across Nevada, a piston blew out the top of the engine, through the hood, and up into the sky, where it disappeared from sight. Since gasoline was so cheap at that time, the hassles and hazards involved in building

experimental cars outweighed the disadvantages of buying gasoline, and they built no more air cars.

George suggested I get around the problem of converting existing engines to run on air, by using a 100 horsepower turbine air motor, which he said would weigh only 25 pounds. My later research turned up the 51A turbine air motor made by the Tech Development Company of Dayton, Ohio, which fits George's description very closely.

I left George's home with a head full of ideas, but without the background to put them to use, or even to properly research them. Because I didn't know how to confirm or deny George's claim to have developed a self-fueling engine, and because he wasn't interested in discussing it further or helping me develop the concept, I eventually came to assume that he must be exaggerating, or dramatizing a hypothetical theory he wanted me to test out for him. But years later, with the discovery of Bob Neal's fundamental patent, my search for the self-fueling air car brought me back full circle, to a working theory that I could almost have written from the notes I took that night at George Heaton's dining room table. The part George left out, the scientific explanation, might have become clear to me if I'd done any research on my idea of running cars on loudspeakers. If I'd studied the theory of sound waves more thoroughly when I was in piano tuning school, or when I was working in the pipe organ factory, it would have been obvious what I had to do to manifest the ideas that George left with me. In the meantime, believing that I didn't know how to design a self-fueling air car led me on a fascinating search through the nooks and crannies of compressed air history and pneumatic options. Each stumbling block along the way turned out to have not only a solution, but an exciting solution that often turned out to be an advantage. I could know only so much about compressed air before becoming permanently interested in it. Each new finding has revolutionized my conception of what compressed air can do. Some of the most often-mentioned of compressed air's supposed disadvantages have turned out to be—from a new point of view—real advantages, and even sources of power.

Interviews with Bill Truitt

March 30, 1986

After more than six years of collecting information on compressed air and air cars, I sat down with my files to start putting a book together. In going through the array of tidbits in my collection, I ran into some flyers that a friend had sent me, which described the work of Willard Truitt of McKees Rocks, Pennsylvania. Bill Truitt is a retired designer and builder of race cars. He also invented a flame-thrower and a wind-indicator for artillery during World War II, and had a career in radio broadcasting.

I'd first heard of Bill Truitt's Pneumatic Electric Air Car when I read a book on alternative cars, <u>Auto Engines of Tomorrow</u> by Harris Edward Dark. Dark included a paragraph on Truitt's air car towards the end of his book but said nothing about how far the car could go between fill-ups. I always assumed that, since the car used electric pumps to make its fuel or part of its fuel, it would only be able to go a few miles before running out of air. This is what an engineer would tell you on first thought. Once I'd gotten Truitt's phone number from information but never called him. I saw no reason to research designs based on hope that perpetual motion might be found in compressed air. For years I'd been

looking for practical ways to increase the efficiency of compressed air used in motors, and ignored any theory or claim that seemed to contradict the accepted laws of physics.

So on March 30, 1986, when I decided to go ahead and call Bill Truitt, in case I had anything to learn from him I almost forgot to have a pencil along for taking notes. When Bill started talking about his sixty-six years of off-and-on experimentation with air cars, I was surprised to find myself writing as fast as I could, trying to get every concept down, and wondering why I even cared about recording what I thought had to be exaggerations. But as Bill continued unbidden to reel off what sounded like a description of a real machine, I felt more and more strongly that I wasn't talking to a con man. There was no pushy come-on, nothing for sale, no offers, no intimidation, and no double-talk. He openly admitted that his air car did what engineers thought to be impossible, and I felt he was trying to inform me if I wanted to learn, but he wasn't trying to convince me of anything.

The only time I thought Bill's answers were vague was when I asked about the laws of physics. His explanation of "how he got around the Law" was that his system comprised three separate units: engine, compressor, and electrical charging system,

> Auto Engines of Tomorrow, Harris Edward Dark, Indiana University Press, 1975
>
> The Pennsylvania air car gets its "charge" from an electrically-driven air pump that builds up a tankful of compressed air, which is used to propel the vehicle by means of air motors. Designed and owned by W. "Bill" Truitt of McKees Rocks, who formerly built racing cars in West Virginia and Ohio, the present-day air car is a development of Truitt designs that go back to the 1920s. The car Truitt was displaying in 1974, the "Pneumatic Electric Air Car," had been road-tested on the streets of McKees Rocks for more than eight months. The car is of compact size and has a heavy-duty plastic body with three interchangeable roofs that can convert the car from a sports model to a station wagon to a conventional sedan configuration. Truitt claims a maximum speed of 50 mph with the powerplant, a two cylinder V-type engine powered by compressed air from three tanks, one of one thousand pounds per square inch and two of two thousand pounds per square inch maximum pressure. The car has instant-start capabilities, and the engine runs almost silently, with its only noise, an exhaust hiss, dampened by a special muffler.

whose separateness somehow made possible the anomaly of a car making its own fuel. The design included electric heaters on the colder parts of the air pipes, such as elbows, where freezing can occur. Bob Neal also heated the air in his engine on its way to the engine. Another explanation Truitt offered was that "It isn't horsepower," though he didn't know what else to call it. He responded positively to my suggestion that maybe it was torque, since air engines, like steam engines, have better torque characteristics than do internal combustion engines for running cars. However the highly advantageous torque characteristics of air engines aren't enough to explain self-fueling air cars. Another place Truitt indicated I could look for explanations was in his "leakproof valve," without which he said the car couldn't work. I have therefore evaluated his mysterious valve as if it worked like Bob Neal's equalizer, in the chapter on acoustic power. Truitt's statement that his secret valve "works like a heart" suggests that it could be some kind of two-stage pump that injects pulses of air into a circuit of moving fluid. The other clue I got in

response to my repeated requests for lawful explanations was that the key was in how once the wheels are going, you have the whole momentum of the car to tap into. This source of energy could not account for any self-fueling capacity, but it could be a way of regenerating some of the losses during deceleration and downhill travel.

The components I describe below are the ones Bill used in one or more of the three vehicles he converted to run on compressed air. His first air car, which he built in 1920, was a Stanley Steamer, with an air engine made from a motorcycle engine. He also converted a Buick Skylark and a Rolls Royce. Though all of these cars were self-fueling, his designs improved over the years till he'd gotten it "pretty well whipped" from 1974-1980.

Bill Truitt holds a drawing of the air car he had to tear down to keep people from stealing it.

For an engine, Bill recommends a two cylinder refrigeration compressor from a large refrigerator truck. He replaced the steel piston rings with neoprene rings, which last 60,000-80,000 miles. The engine could be installed in 35 minutes. The valve could be changed in 30 minutes. The engine ran on 86-125 psi air. The car was so fast it was scary to drive; Bill once had it up to 136 mph. It was extremely powerful and accelerated too quickly for someone used to driving gasoline cars, so Bill put a limiter on it so it couldn't go over 55 mph. The engine drove the axle through a fluid clutch, a hydraulic drive like a torque converter that slips at speeds up to 300 rpm. Apparently this device solved some serious design problems. Top engine speed was about 1200 rpm. The engine used air non-expansively, that is, the air entered the cylinder throughout the whole piston stroke and exhausted in a still-pressurized state. The engine did not idle. It went right in front of the differential.

The compressor was the heart of the machine. It went under the hood where the gas engine used to be. It was run by a 24 volt DC motor which got its power from two 12 volt car batteries which were charged by two automotive alternators, which were run by pulleys off the engine shaft. The compressor was three-stage, capable of pumping the car's three "acetylene-sized" tanks up to 5000 psi in 14 minutes, but was used to fill them to only 2000 psi. A pressure switch would turn the compressor on when the pressure in the tanks got down to 1000, 1250, or 1500 psi, depending on terrain. In hillier driving, the compressor came on more often, with the pressure switch set to maintain a higher minimum tank pressure. The Mako compressor he used cost him about $1600 at the time. It ran at about half the speed of the engine, and only about a tenth of the time the car was running.

Truitt used several small "worm-drive hydraulic air pumps." These pumps were easy to replace, as they slid onto a shaft run by the differential. These pumps put air into the tanks at all times while the car was running. More pumps were required in mountainous terrain, the maximum being 10-12. Because it seems unlikely to me that these pumps could put out 1000-2000 psi, I believe they were putting out low pressure air which his secret leakproof valve managed to get into the tank, using the movement of air on its way out of the tank as the power source for the entrainment of the low pressure air from the pumps. This is speculation on my part, based on Bob Neal's patent.

When I asked if I could visit him in McKees Rocks, Bill changed the subject and started talking about harrassment he'd gotten from the powers that be, including Exxon. He said the Japanese car companies would send spies to accost his friends and try to get his secrets out of them. The U.S. car companies had his phone tapped. Finally to stop this harrassment he sold the car and the right to make the car to the U. S. Army and NASA, for a .1% royalty for himself or his heirs. The Army has built air powered tanks, Jeeps and a helicopter using Truitt's designs.

Bill says the Army generals who are working to develop air powered weaponry have decided that the public isn't ready for cars that have an unlimited range between fill-ups and cost nothing for fuel. He thinks it would hurt the auto and oil companies too much if air cars were introduced now, and wants to give the U.S. automakers a chance to catch up with Japan so Japan won't corner the air car market. He speaks of a future where we could have Chrysler air cars, Ford air cars, etc. Bill is satisfied to let the revelation of his secrets happen "at the government's pace." The Army is supposed to build a model air car for the automakers to copy. He's told me in writing and over the phone, when I asked for the whole truth, "The rest is Top Secret."

When Bill Truitt was about 17 years old, he built his first self-fueling air car with his father's help. His father was in the car or gasoline business. When the car worked, Bill's dad asked him to keep it quiet, because it might hurt business if word got out. Although there have been times when he was getting sacks full of mail wanting to know about air cars, somehow Bill has managed to keep it quiet for 67 years.

After my first interview with Bill Truitt, I kept thinking about the separateness of the air car components from each other that comprised his first explanation of why the car wasn't breaking the laws of physics. After a few months of seeking and not finding loopholes in the laws of physics, I came to the realization that the secret had to be in some property of compressed air itself, and in a means for taking advantage of that property; a loophole in the laws of physics would show itself in the behavior of all cars, and would have become generally known long ago.

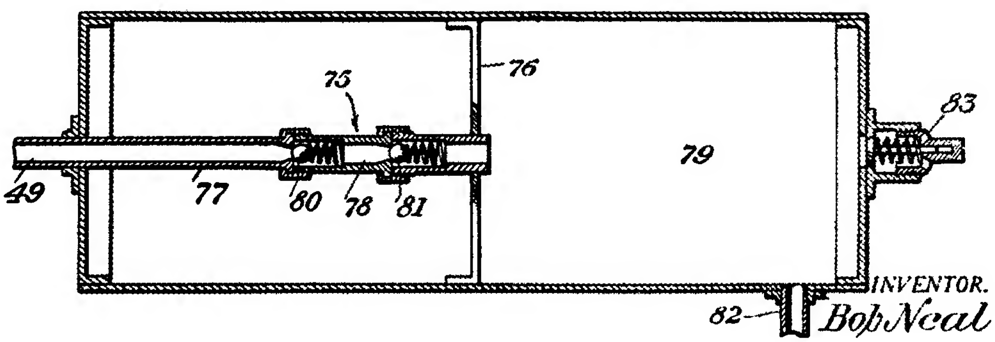
Interview with Bob Neal's Son

October 14, 1988

(Floyd Neal started right in describing the engine hardware in some detail. I got my tape recorder hooked up while he was talking, and steered the conversation toward the equalizer, or "special valve" in the tank.)

SR: Did you see the inside of the tank where that one special valve was?

FN: Now he had a special valve where he could load the tank with very little pressure. That was a—the valve looked like an extremely skinny, long plumb bob. That's about all I can remember, like I say, I was just a small boy.
SR: How old do you think you were? Maybe 16 or so?
FN: Oh no, I was younger than that. Oh, probably maybe seven or eight years old, and probably the last I had anything to do with it, 'cause I was out going to school, probably maybe 13 to 15 But I couldn't really give you any good detail.
SR: Do you know about how long or how big the tank was?
FN: Well the storage tank was a streetcar tank. If I remember right they were probably about 16 inches by probably 4 feet.
SR: Pretty big tank, huh?
FN: Yes, the reason he used that, it was available, You probably wouldn't have to have that big a tank. As far as that goes, it was actually just to start it with. 'Cause then you see it starts producing air on its own.
SR: Do you know what the principle is of being able to get the low pressure air into the tank?



FN: That was, he felt, the valve. It was a type of valve that—it was a double valve of some sort.
SR: Double check valve according to the patent.
FN: Yeah, and you could load the tank with a lot less pressure than was in the tank.
SR: Did he ever talk about water hammer or pulsejets?
FN: No...
SR: You know when your water pipes start buzzing, vibrating in the wall, that kind of principle is what makes pulsejets work, and I was thinking possibly it was similar to that.
FN: I couldn't really tell you. Have you come up with anything that you're working on?
SR: Well no, I'm just a researcher, and this is so far the only patent I've found that actually said what it was trying to do. It doesn't say what the working principle is but I think I've figured it out. I think if you make the air vibrate, then it organizes itself into high pressure zones and vacuum zones, and the vacuum waves can be used to let that low pressure air in. So it's kinda like a ram pump, and pulsejets and other wave-type machines that work on causing the fluid to vibrate and make waves. So that's what I think it is, it seems to make sense to me, and that's what my research seems to lead to.
FN: Well it's important to get that research. Have you actually developed any kind of engine?
SR: No, what I've got is, I've built the tank and I put the two check valves inside the tank, sorta like the way it looked in the patent, and I've got an air motor running a rotary

compressor, to put the low pressure air in. And I'm getting low pressure air into the tank all right—[*]
FN: About what kind of pressure?
SR: About maybe ten pounds—I can get it in at two pounds but if you run the air motor faster it pumps it up to a higher pressure. It's still going in at a *much* lower pressure than what's in the tank. So I think it's working, and I think having the compression and engine cylinders on the same crankshaft is the secret. That's why I'm running the compressor direct with the air motor, so they're going at the same speed.
FN: Sure.
SR: Yeah. I think that's your dad's trick is to have the pulsations entering and leaving the tank at the same time so you just have that very clear, distinct wave in it.
FN: Does Mr. M. have a picture of the engine?
SR: Well he says he's got an article but he says it's off in a box somewhere and he doesn't even know where to start looking for it.
FN: I thought he might have a photograph. Of course you're trying to discover something that's altogether different?
SR: Well, yeah, I'm mainly sort of an air car advocate you might say. I'm exploring the whole area and I'm looking at all the different systems I can find, and so far I think this is the best, and I'm concentrating on it. And hopefully I'd like to build an air car that uses this principle—is the patent owned by someone now?
FN: No, you know, it's run out. It's public domain. I was thinking about, oh a few years back, renewing it, but then it wasn't right for me and I just didn't deal with it and now I have no interest in it.
SR: Well it seems to me like it sort of works similar to a perpetual motion machine, which is supposed to be impossible.
FN: You know, when he patented that thing—he had trouble patenting it. Because they notified him and told him that the United States Patent Office was not interested in perpetual motion. And he fired a letter back to them and told them he wasn't either, he just wanted to patent an engine that was functional. And as a matter of fact he got busy and made a little—a small prototype—a hand carried model. And as a matter of fact I went with him to Washington when I was a little boy, and he put it up on Garrett Whiteside's desk—he was top man at the time—started the thing up, and he called in the investigative men, and they had to issue him a patent. You can't argue with a functioning engine, right?
SR: That's right. Well that's great. So the little model had the tank and the valve and the—
FN: Yes, it had everything and he could actually carry it in.
SR: Well that's pretty good because they say in no uncertain terms that they won't grant one, and there's so many air car patents that—
FN: Yes. Don't ever mention perpetual motion.
SR: Right. Have you ever heard of anybody else that's done something like this with air?
FN: No, I heard there was someone in the South, a couple years ago, but I don't know if it was just rumors or what. But I didn't really know about it.

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[*] I later found that I was deluding myself at this point about my test results. This was my first or second experiment with compressed air, and I later realized that my tank was too small; it would empty as soon as the valve was opened to let air to the air motor, so I was essentially pumping into an empty tank.

SR: What was your dad's relationship with Mr. M.? They were corresponding with each other? Or they were friends?

FN: Well, I don't really know how they got—oh, I know what it—my dad's sister, my aunt, and her husband were living in California somewhere, and I think they were sitting in a city park or something, and the conversation just came up, during the conversation, and my uncle said, well, his brother-in-law was—oh, it was "odd things"—but he said his brother-in-law was working on an engine that ran on air. And Mr. M. heard that, and got interested, and got his address and everything and came down. I remember when he came down. That's how that started. I think that was about '45.

SR: Well I've been working on this research for nine years and someone introduced me to Mr. M. over the phone. We had a three-way phone conversation and he started talking about this and we tracked down the patent. And I thought about it for about a year and a half before I figured out this wave principle for how it might work, and got some research to back it up. I think we're doing pretty good. Would you like to be on my mailing list in case we get something going and put out a newsletter?

FN: Yeah. You know, there was another fellow that was interested in this, that was William Lear. He was kind of interested in seeing an air engine a couple of years ago. He came down to see me a number of times also. And that was over this valve—in the tank.

SR: Did he look at it?

FN: Well, I didn't have it. He came down to my place.

SR: Oh. He's sort of like me, he was trying to get information from you.

FN: Right. And I don't know, he did come up with some sort of an engine—steam, though, I think—and busses in L.A., years ago, and also in police cars. But I don't know.

SR: Was he adapting your father's invention?

FN: Well, at the time, he didn't know if he was gonna go air or steam.

SR: Mr. M. says you had to stop making this or stop developing it because somebody came from some government or something.

FN: That was during the war years?

SR: Uh-huh.

FN: Yes, as a matter of fact, my sister was even kidnapped over it. Germany wanted it real bad. They tried to buy it. And of course my dad didn't do business with foreign powers or the enemy. Then they tried it their way. And they threatened him and said they'd have his family members killed off one at a time. What happened is he dismantled it, and scattered the parts all over the countryside. They just literally scared the old boy to death.

SR: That was the Germans, huh?

FN: Uh-huh.

SR: That's pretty bad.

FN: Yeah. Poor timing for him.

SR: That was right after he got it patented?

FN: Yes. His first engine was a lot bigger. The first one was fourteen cylinders—air compressors—it was a big "V". Then he decided that was too much, and then his last one was—he called it the "Model 39"—it was just half a block. It looked very similar, and the same size, as an old straight-8 Buick, because the hangers and everything would drop right in on a straight-8 Buick. Because that's what he had at the time, and he wanted that to

drop in there, and use the same drive line and everything. The engine actually looked like a letter T.

SR: A letter T?

FN: A letter T. Just straight like an old straight-8 and it was a "V" out front where the two pullers were, set a little off to the side. The crank on that was perfectly round. The pullers had a little larger throw. The engine was basically the same thing cut in two from the original patent. Seven compressors is like fourteen, working both up and down. I remember it, he hooked it up to a machine lathe and had it running that. It worked!

SR: All right. Well I think it'll work because I'm partially showing it myself, a pretty crude, rigged-up system.

FN: Well, have you actually produced an engine?

SR: Well, not an engine, I'm just putting components together, I've used an air motor and I'm running a compressor with it, and I'm having that compressor put the air back into the tank. It's not putting enough back in the tank yet. Does his air motor cylinder—did they use the air pretty efficiently or did they let the air come in through the whole stroke and then exhaust it?

FN: Well, evidently it was efficient but he had no way of using the same air. His engine, I believe it would fill the tank I believe to 140 or 150 pounds and then the excess would escape.

SR: And then the exhaust from the engine just exhausted, right? It wasn't recaptured?

FN: Yeah, just like a regular combustion engine.

SR: Was the safety valve letting air out all the time or only when it was idling?

FN: Well, it maintained that pressure. And if I remember right, I could hear the air leaving all the time, so I think it was producing quite a bit more even under load.

SR: So even when it was running, the safety valve was letting out a kind of a regular spurt?

FN: Yeah. Uh-huh. It made a hissing noise because he didn't muffle it. He just turned it loose.

SR: That could be a key. If the safety valve was letting air discharge all the time, then that's important because it could be causing the pulsejet effect. Sudden discharge like that—when you suddenly let a burst of air out through your safety valve—can create a vacuum inside the tank.

FN: Sure. That's what it is, it's one of the features. That 's what he said, "The valve is the feature." And like I said, as a small boy, I was thinking of other things.

SR: Right. Well, those are pretty much the questions I had for you, I really thank you for taking time with me.

FN: Well, I wish I could help you more, I just can't remember the finer details.

SR: Well, that's fine, I think that the patent's pretty complete, but they just left the working principle out. It's probably just patent lawyers' tactics, you know.

FN: Yeah, sure. That's the legal people for you.

SR: Yeah. All right, Mr. Neal, I appreciate your taking time with me.

FN: Well I appreciate talking to you. Hope it works out.

Chapter 10: Regeneration Schemes

Conserving Compression Heat and the High End of Storage Pressure

"Cost-effectiveness aims at optimizing all parameters; and more particularly instituting savings when possible. It is, for example, possible to achieve near 100% overall efficiency with a compressed air installation. This can be done by recovery of the compression heat generated in the production of compressed air."

(Pneumatic Handbook, R. H. Warring, 6th ed., Houston: Gulf Publ., 1982, p. 50.)

"Adiabatic compression of air to 100 psi results in outlet air temperatures of 350-500° F. When this air is cooled to ambient temperatures, 60-90 percent of the energy of compression is removed, and this can be used for other purposes. This heat is a low grade source that is available year round whenever the plant is in operation. Typical uses of the air include supplemental space heating, boiler makeup water preheating, or process heating.

"If a regular all season use of this low grade heat source is available, the heat recovery system efficiency considerations are of greater importance than the compressor efficiencies discussed in section 4.1. Since nearly 80% of the input energy is available as heat, the 20% energy content of the compressed air is nearly a by-product. In multiple compressor systems, the compressors could be located near each of the locations requiring space heating to minimize the ducting requirements, air pressure control stability considerations permitting."

(Compressed Air Systems: A Guidebook on Energy and Cost Savings, E.M. Talbott, Atlanta: Fairmont Press, 1986, p. 77-79.)

Haupt on Injectors

"It has been found that whatever may be the pressure of air in the motor tanks beyond a certain very moderate excess above the working pressure, the additional power expended in compression cannot be made available in propulsion, but is lost in wire drawing the air through the reducing valve to a lower pressure. Consequently all the power expended to secure high pressures in the reservoirs serves only to increase the tank capacity and the length of run.

"To avoid this loss, compound engines have been tried, but they are not only unsuited for small motors in consequence of complication, but they have failed to accomplish the object.

"Another plan of utilizing the high pressure has been proposed by allowing it to escape through an injector, and thus forcing an additional volume of fresh air into the motor cylinders, reducing to that extent the draft upon the reservoir. It is not known that this plan has been tried, or, if tried, what has been the percentage of gain."

(Street Railway Motors, Herman Haupt, London: Henry Carey Baird & Co., 1893.)

Hudspeth & Lunsford's Air Pulsing System

Like Bob Neal's patent, the Hudspeth & Lunsford patent relies in part on what Neal's patent calls a "constant reserve tank pressure" which is manipulated to induce atmosphere which mixes with the stored high pressure air. Two advantages of doing this are that the high pressure is not thrown away in reduction through a regulator, and the ambient heat contained in the atmosphere is essential in any self-fueling pneumatic power plant. Also like Neal's patent the Hudspeth & Lunsford design makes use of wave processes to increase the pressure fluctuations that are used to induce atmosphere. This part of their design will be taken up in the chapter on acoustic power.

Hudspeth & Lunsford received two patents on their air car; one for the air pulsing system, and one for the regenerating shock absorbers as described later in this chapter. The air pulsing system is similar in concept to the Pratt oscillating/linear air engine described in detail below, though it doesn't include a heat exchange system as Pratt's system does. Pratt's air engine doesn't make use of acoustic wave processes.

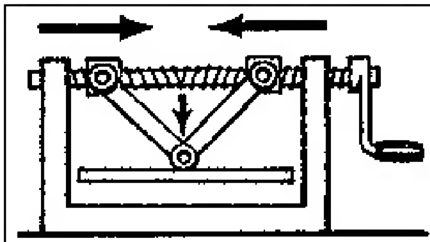
The quote below is from a Rex Research Folio on air cars:

> <u>Notes by T. F. E. P.</u>
>
> ...energy is neither created nor destroyed. This seems to be in agreement with (an article about Lee Rogers' self-fueling air car)...Such a compressed air power source offers the means to utilize energy through manipulation, without dissipating or expending it. The power needed to recompress is minimal because such recompression is not from atmospheric pressure way back up to tank pressure. In the power stroke little decompression takes place compared to the amount of air and the pressure of it available in the tank. In other words the energy required to perform the power stroke in addition to the amount of energy required to recompress after the power stroke is a very small amount compared to the amount available in the supply tank. The problem then becomes not wheter or not there is enough power available. Clearly the only problem is in developing the hardware necessary to manipulate the available energy without letting it slip through our fingers.

U. S. Patent No. 768,691, Air-Engine, Patented Aug. 30, 1904, by Wilson R. Pratt of Topeka, Kansas.

(excerpted and paraphrased by the editor)

Object of invention: to use the stored high pressure air during its reduction to low pressure as initial energy for the compression of free air; eliminating the usual practice of wasting this high pressure by reducing the air pressure in a regulator; to increase the economy of both air engine and compressor by exchanging heat and cold between them.



Toggle joint

***"Any of various devices consisting basically of a rod that can be inserted into an object and then**

Comprising: an oscillating high pressure air engine cylinder, and a linear low pressure air engine-compressor unit, amounting to a single-stage compression and a two-stage expansion, wherein the cold of expansion cools the compressor cylinders while the heat of compression warms the engine cylinders. The high pressure engine cylinder also acts as a toggle-joint* which exerts its extreme of stress at a time when most required in the compression of free air. The air compressors as devised constitute a component part of a compessed air vehicle wherein high pressure compressed air in storage forms the initial energy.

Lettered Components, Figures 1-8:

A A', linear engine cylinders, low pressure stage
B B', linear compressor cylinders
A" B", annular open spaces (jackets) formed in the casings of engines *A A'* and *B B'* respectively (Fig. 1)
C, oscillating engine cylinder, high pressure stage
C', step elevating cylinder *C* from base *Z*
D D', semirotating engine valves; intake and exhaust, respectively
E, conduit pipe which initially admits high pressure air to the system by way
E' E", pipes which take air from pipe E and distribute it to the jackets surrounding the compressor cylinders
F F', conduits which deliver high pressure air to primary engine cylinder *C* after it has cooled the compressor cylinders by passing through their jackets
G G', intake and exhaust pipes, respectively, of high pressure cylinder
G" G''', pipes from high pressure engine exhaust stuffing box to intake valves of linear engines
g h g' h', toggle-joint dead center points; see dotted lines (Fig. 2) showing positions of piston rod O" at the two extremes of its oscillation; Fig. 2 shows O" at the mid-point of its oscillation, halfway between the dead centers
H, exhaust pipes leading from the compressor cylinders to the warming jackets A" surrounding the low pressure engine cylinders
H'H", exhaust pipes carrying cooled compressed air away from linear engine jackets to the vehicle's drive tank which supplies air to the drive engine of a pneumatic vehicle

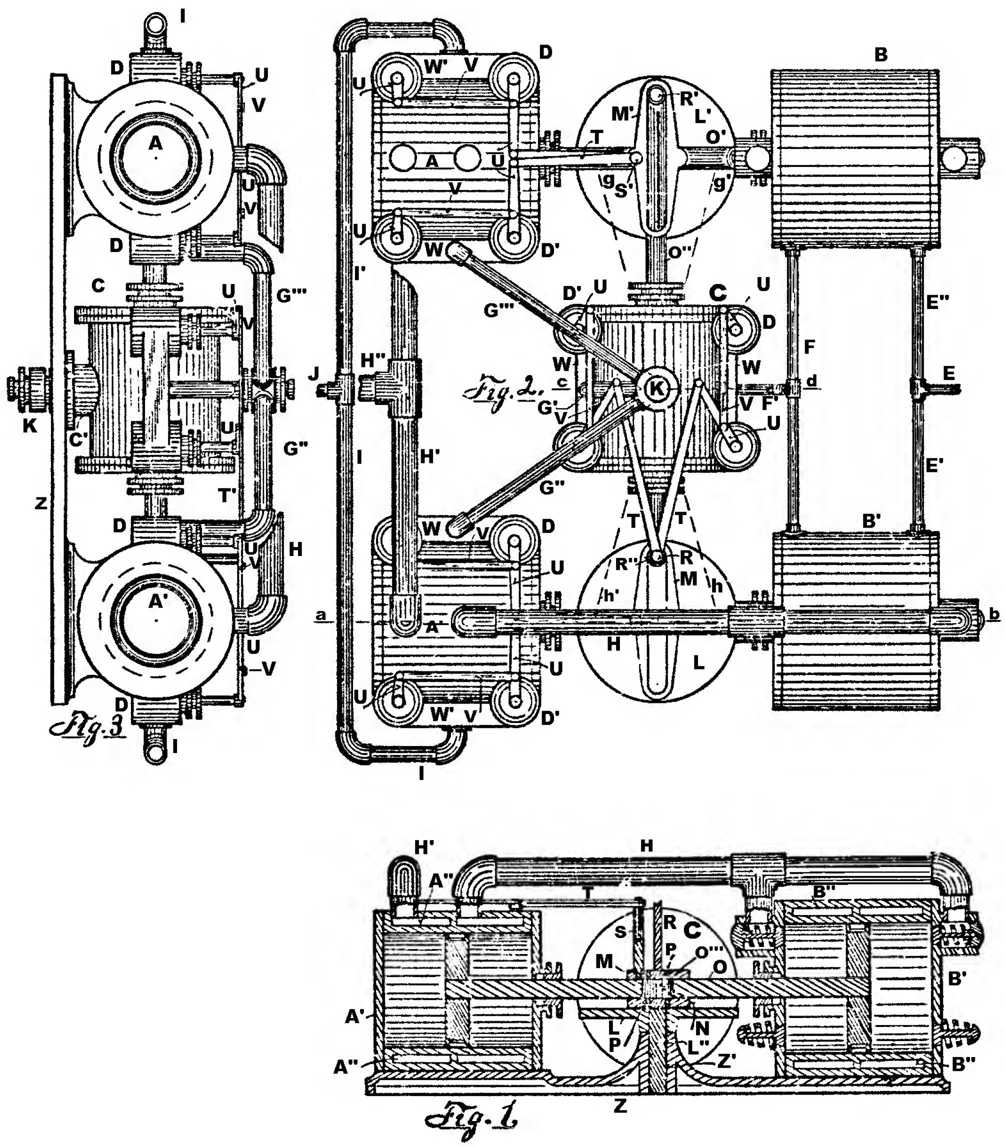


Fig. 1.—Sectional view taken through the line *a b* of Fig.2.
Fig. 2.—Plan view: general arrangement of compressores and engine, excluding base.
Fig. 3—End view or elevation of Fig. 2.

I I', exhaust pipes of linear engines

J, final engine exhaust pipe, fed by pipes *I I'* and leading to a low pressure tank for conservation of any remaining pressure, or to the atmosphere

K K', stuffing boxes for high pressure cylinder

L L', crank-disks of high pressure engine

L", studs on which crank-disks rotate

M N M' N', double-bow stirrups in which play the crank pins *R' R"*

O O', piston rods connecting linear low pressure engine-compressor units

O", piston rod of high pressure cylinder

P, antifrictional roller on the disk crank-pin (Fig. 1)

R, stud moving with the piston rod and extending upwardly from the crank-disk pin R"; the first part of the linkage also comprising *T T'*, *U*, *V*, and *Y*, that causes the semirotation of the valves that control high pressure engine *C*

R' R", crank-pins of high pressure engine, connected to the two ends of piston rod *O"*

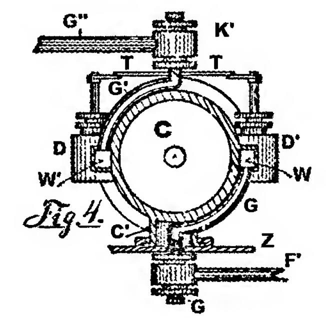


Fig. 4.—Transverse section taken through the line *c d* of engine *C*, Fig. 2.

S S', studs rising from the double bow stirrups; like *R* above, but in the low pressure engines

T T', valve rods in the valve-operating linkages

U, valve levers in the valve-operating linkages

V, connecting rods in the valve-operating linkages

W, port of conduit *W'* opening into engine valve chamber (Fig. 5)

W', conduit (see Fig. 5) that connects the valve to the engine cylinder

Y, valve dogs in the valve-operating linkages (Fig. 5)

Z Z', base and its bearing, respectively, in which studs *L'* operate

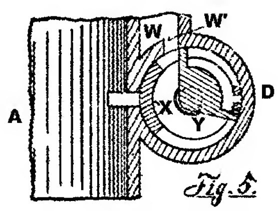


Fig. 5.—Transverse section of valve-chest, taken through line *e f*, Fig. 3.

Operation of the Engine:

High pressure cylinder *C* oscillates back-and-forth between the extreme positions of its double-ended piston rod, marked at dotted lines *g h g' h'*, as these positions would be seen from above (Figure 2). This is in reference to the positions that the line of piston rod O" would lie in as seen from above, not the positions of the piston within its stroke. The rotation of the crank disks *L L'* are caused by the combined reciprocations of the three piston rods: high pressure engine, low pressure engine, and compressor. The linear low pressure engines push the compressor pistons through the first 3/5 of their stroke, then the high pressure engine completes the compression work, pushing the compressor pistons to the end of their stroke and through the linear dead center. At this point the linear engines take over on their return stroke. There are two dead centers in the unit: the toggle-joint dead centers shown by the dotted lines *g h g' h'*, and the dead center of the linear engine at the extremes of its stroke. The linear engines take over when the oscillating engine is at dead center, and the oscillating engine takes over when the linear engine is at its dead center. In rotary engines, dead center is overcome with flywheels, cam advance, etc.; this is not a rotary engine so the cooperation of the oscillating and linear engine has been devised to keep the engine from stalling. Dead centers are caused by a piston pushing from an angle at which it has very little or no torque to turn the crank. A push at 90° has maximum torque.

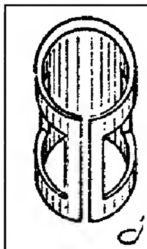


Fig. 6.—Perspective of the valve

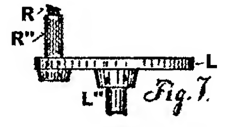


Fig. 7.—Detail of crank disk and crank pin.

Since my understanding of Mr. Pratt's ingenious engine is less than perfect and my interpretation of its working could be mistaken on some points, I will now quote directly from his patent so that my paraphrasing can be checked for accuracy:

"...The oscillating primary engine is a portion of the mechanism constituting a toggle-joint which exerts its extreme of stress at a time when most required in the compression of free air....The rotation of the (crank-disks) is secured by the combined reciprocations of the piston-rods, *O*, *O'*, *O"*, the oscillations of the engine *C* being shown by the dotted lines *g h g' h'*. The disk crank-pins *R' R"* play in the double-bow stirrups *M N* and *M' N'*, and in the rotations of the crank-disks, produced, as described, by the reciprocation of the piston-rods of these engines, the extreme of pressure in the air-compressors is overcome by the oscillating primary engine *C* by exerting the extreme of its power in forcing the crank-pins *R' R"* over the toggle-joint centers *g h* and *g' h'*. The dead-centering points of the toggle-joints being passed, the straight line engines take up their work of performing the first three-fifths of the stroke. As an antifrictional device the roller *P*, (see Fig. 1,) may be placed on the disk crank-pin."

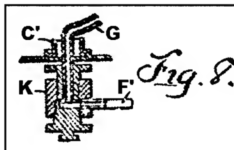


Fig. 8.—Detail sectional view of one of the valves.

I assume that one of the intended functions of this device is to avoid the use of the 360° crankshaft by eliminating rotary motion. For more information on crankshaft substitutes, and why the crankshaft is less than ideal as a torque transmitter, see the chapter on alternative engines.

Regenerative Braking

"Under favorable circumstances, a vehicle engine capable of developing 100 horsepower may accelerate the vehicle to 60 mph in one minute. The brakes of the vehicle, however, must be capable of stopping it in approximately one-tenth of this time, or about six seconds. The comparative horsepower then required to stop is 1000 horsepower.

"The kinetic energy developed by the weight and speed of the vehicle is converted into heat energy by the friction of the brake drum and shoe. This heat is dissipated into the surrounding air."

(Automotive Fundamentals, Irving Frazee, Chicago: American Technical Society, 1949)

Increased Power from Motor Cylinders Acting as Air Pumps.

The motor cylinders are so arranged that in descending steep grades they act as air pumps, and at the same time as brakes, by which means it is found, as stated by the company's engineer, Mr. Hardie, that in running down grade on the Second Avenue Railroad, pumping back against a pressure of 200 pounds in the receiver, the pressure was increased 7 pounds in a distance of 0.4 mile. As it requires 360 cubic feet to run one mile, 0.4 mile would require 144 cubic feet.

If the pressure were increased 7 pounds in a receiver containing 160 cubic feet at 200 pounds, the air pumped back would have been 5.3 cubic feet at 200 pounds in 0.4 of a mile, equal to 69 cubic feet at atmospheric tension, which is about half the amount of air that would have been expended in running an equal distance with the aid of the heat on a level, with a consumption of one cylinder of air at each stroke, but with actual results 50 per cent. greater.

To appreciate the importance of this result, it must be observed that not only is all the air saved in running down hill and not a particle used, but half as much or more as would have been expended with the aid of heat and vapor upon a level is pumped back again, and at the same time the action of pumping back acts as a most efficient brake, the efficacy of which is spoken of by the intelligent mechanical engineer of the Delamater Works in terms of the highest commendation

When a locomotive engine shall, while running, be able to manufacture coal and store it in the tender, it will then be able to rival this performance of the pneumatic motor.

This is certainly a most extraordinary result, and so large a percentage of gain is only possible in consequence of the great expansion in the motor cylinders The air and vapor escape at the tension of the atmosphere, without the noise which attends the escape of high pressure steam. When the air at atmospheric tension is pumped bank again, it can readily be perceived that a certain percentage of the power expended will be restored, since only half a cylinder of air or less is required to do the work at each stroke

Such a contrivance can only be characterized as admirable, and, it will be perceived, adds another considerable percentage to gain in coal as compared with steam motors.

When a locomotive engine shall, while running, be able to manufacture coal and store it in the tender, it will then be able to rival this performance of the pneumatic motor.

It has been shown that at atmospheric tension the contents of the motor cylinder are just one cubic foot for each revolution of the car wheels and that there are 720 revolutions per mile. There should be pumped back therefore 720 cubic feet if the inclination were steep enough to employ full power, which is found by computation to be 198 feet per mile, and when heated, saturated, and expanded, this air should run the car two miles or more, instead of one. In other words, while running down hill one mile, on a grade of 198 feet, the motor theoretically might store up enough to run it two miles on a level; and recent experiments have shown that 50 per cent. may be added to this estimate.

(Street Railway Motors, Herman Haupt, London: Henry Carey Baird & Co., 1893.)

Regenerative Shock Absorbers

Many air car inventors have patented systems of compressing air with the vehicle's shock absorbers. This is not a bad idea. But is it accurate to call this a "source of energy"? A "source" must be external, with the power derived from something other than the car's motion. The vertical bouncing of the car is not in itself a free source, since

driving over bumps or out of dips and potholes robs power that could have been used for driving forward.

There is, however, another consideration: the air being compressed is a source of solar energy. This changes everything! Any means of getting atmosphere into a pressurized tank cheaply is a source of solar heat that compressed air is uniquely qualified to exploit. Since the bumps and dips exist, there's nothing wrong with putting them to use...*if necessary*. Many have claimed to achieve self-fueling working of their air cars without resorting to complications such as this.

Here is a list of patents issued to inventors for regenerative shock absorbers:

Patent	Date Granted	Patentee	Title of Patent
684,953	October 22, 1901	William Singer	Pumping Device for Automobiles
887,505	May 12, 1908	Wesley Nelson & Lee W. Galloway	Air-cushion and Air-compressor for Automobiles & Other Vehicles
1,337,501	April 20, 1920	V. Arluskes	Compressor
1,469,140	Sept. 25, 1923	Edward Baisden	Pump
1,862,195	June 7, `1932	Ralph L. Newton	Automatic Pumping Mechanism
2,049,010	July 28, 1936	Erwin C. Horton	Motor Vehicle
3,507,580	April 21, 1970	Landon Howard & B. Howland	Energy Generator
3,527,188	Sept. 8, 1970	John D. Shepard	Power-Producing Means for Vessels
3,688,859	Sept. 5, 1972	Steve Hudspeth & John Lunsford	Vehicular Air Compression System
3,861,487	January 21, 1975	Walter L. Gill	Electric Power Means for Vehicles
3,921,746	Nov. 25, 1975	A. J. Lewus	Auxiliary Power System for Auto. Vehicle
3,980,152		Robert T. Manor	Air Powered Vehicle
3,981,204	Sept. 21, 1976	Ray. E. Starbard	Shock Absorber Drive Unit
4,295,538	October 20, 1981	A. J. Lewus	Auxiliary Power System for Auto. Vehicle

Recapturing Losses Due toWind Resistance

The Windmill on Wheels

The idea of putting a wind turbine in a car to generate power was first presented to me in 1973, on a paper napkin at a pizza parlor. Since then I've discovered several patents on the concept.

The same criteria must be used in evaluating this concept as with regenerative shock absorbers or any other complication that hopes to improve on the air car's range and/or efficiency. Is a source of energy being made available, or is it just going to tax the car's limited air supply trying to "create" energy? Is the added weight, cost, and complication of more moving parts worth the trouble, or are they even needed? Is there a simpler way to do the same thing?

The wall of air in front of a moving car was put there to slow us down, but greedy humans that we are, we must drive around as fast as we can, guzzling coffee with our gasoline. Now that we are considering running our cars on the very stuff that creates the greatest drag on the car's motion, can this drag—a form of compressed air—be converted into the contents of the fuel tank? How big of a windmill does it take to make it worthwhile? Does a larger windmill take in more power, or does it just slow the car down more?

In aerodynamic design, the first objective is to present the smallest possible effective surface area as an obstacle to the wind. This is done by streamlining, or cutting the corners off the car's body and sloping everything back away from the wind, so that the air can slip over the car instead of slowing it down. So putting up a bigger windmill would be counterproductive; for every unit of power you can regenerate, you lose more than one unit of power. So the best way to deal with drag is to eliminate as much of it as possible. So if you want to install effective wind turbines, they won't be very big, which means they won't do much work; in windmill design, size is a very meaningful factor. Greater surface area and facing directly into the wind are the keys to getting any power out of it.

The other main factor is wind speed. And remember, this is not solar wind; it's wind created by the relative motion of the car and the atmosphere it's attempting to plow through, at great expense to fuel reserves.

As stated in the chapter on power requirements, aerodynamic drag on a moving vehicle increases to the square of the vehicle's speed. This is why drag is negligible at 20 mph, and devastating at 60 mph: if you double the car's speed, you increase drag four times; if you triple the speed, you increase drag nine times; if you drive four times faster, you need sixteen times the fuel to overcome drag.

But when it comes to windmill design, there are three categories of wind speed: too little, just right, and too much. *Too little* wind doesn't overcome the start-up friction of the turbine and the power generating equipment that the turbine has to drive. *Too much wind* is dangerous; windmills are designed to turn out of the wind when it's moving as fast as we drive our cars at the speeds where aerodynamic drag becomes an issue. *Just right* is a mighty short range of operations, especially when you put one of those noisy things in a car. It might shake the car to pieces trying to get a little air into the system, then have to get shut off just when it starts doing some good. Or the whole car might take off like a helicopter, or due to the gyroscopic forces you may try to turn right and find the car going to the left.

In summary, if your heart is set on traveling under wind power, get a sailboat!

Here is a list of patents issued to inventors for regenerative wind absorbers:

Patent	Date Granted	Patentee	Title of Patent
3,374,849	March 26, 1968	Lawrence Redman	Electric Vehicle
3,444,946	May 20, 1969	Nelson Waterbury	Self-Electric-Powered Vehicle
3,556,239		Joseph W. Spahn	Electrically Driven Vehicle
2,126,963	April 4, 1984	Roger S. Brierley	Air Powered Electrical Vehicle (British patent)

The Air Drag Cancelling Nozzle

I have a better idea, and it's no more far-fetched than bolting a windmill to the roof of your air car, or finding room for it under the hood.

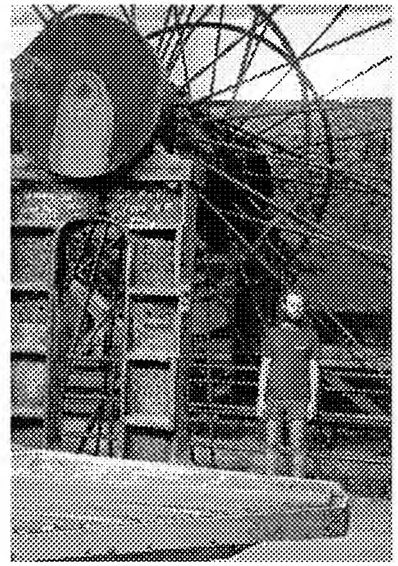
While the front of the car is ramming air into a compressed state, the air behind the car is being pulled into a rarefied state; a suction or partial vacuum exists behind a moving car, literally pulling it backwards. This is an interesting state of affairs. Aerodynamic drag is composed of relatively high pressure air in front of the car and relatively low pressure air in the back. Why not put scoops on the hood and roof, run pipes around to the back, and dump the air through nozzles into the void behind the car, thereby emptying the pileup to fill up the emptiness. This simple ducting system includes no moving parts, and is itself

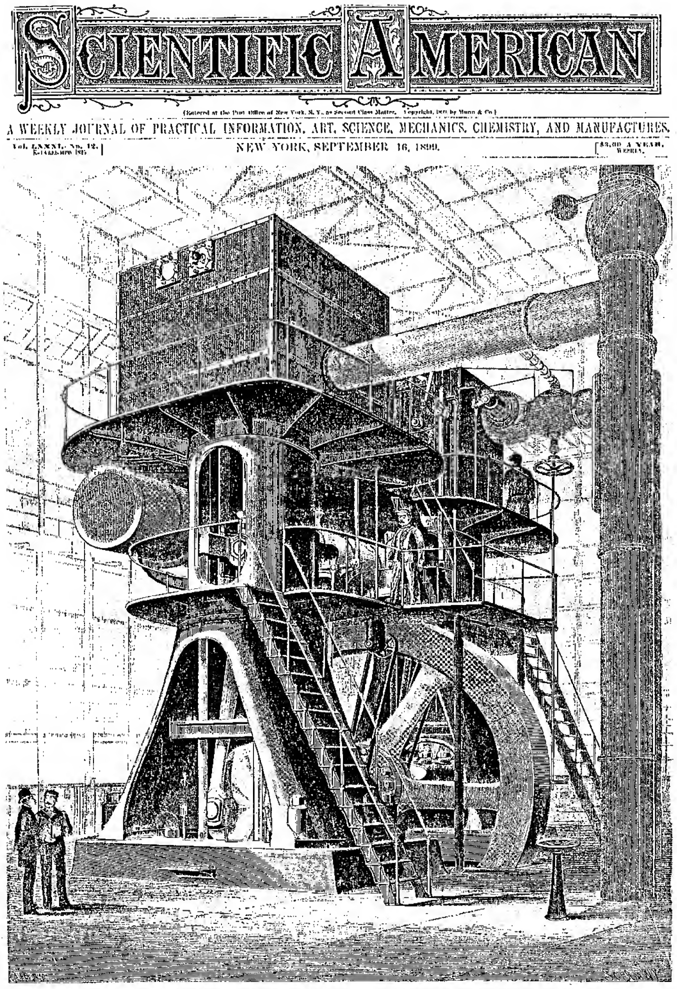
conducive to streamlining, working *with* aerodynamics instead of *against* them. According to the inventor of the jet engine*, ram compression can reach 100% efficiency. Ram compression is used in the ramjet, a jet engine with no mechanical compressor. The explanation of this occurrence of 100% efficiency is that there are no moving parts in such compression, the air is used immediately before the heat of compression can dissipate, and there are no conversions involved from one form to another; the air thus compressed is not being used to generate something else, it's being used as compressed air. I know of only one other case where I have read that 100% efficiency is normal, and that is with electric resistance heating. So next time you make toast, think about this:

***'Ram' Compression and Intake Design**

Except at take off and low subsonic speeds, for reasons which will be given below, the efficiency of ram compression is very high at moderate and high subsonic speeds if the axis of the intake differs little from the line of flight, i.e., in the absence of yaw or other aerodynamic deflection of the air at intake entry, and there is no error of significance in assuming that the efficiency of ram compression is 100%.

(Gas Turbine Aerothermodynamics, Sir Frank Whittle, Pergamon Press, 1981)




SCIENTIFIC AMERICAN

A WEEKLY JOURNAL OF PRACTICAL INFORMATION, ART, SCIENCE, MECHANICS, CHEMISTRY, AND MANUFACTURES.

NEW YORK, SEPTEMBER 16, 1899.

COMPRESSED AIR TRACTION IN NEW YORK CITY—1,000 HORSE POWER COMPRESSING ENGINE.—[See page 184.]

AIR CARS IN 1899

Left: This 1000 horsepower compressor was run by a steam engine, and provided compressed air for the pneumatic transit locomotives running in New York City at that time.

Above: Another 1000 horsepower compressor was in use at the North Star Mine Powerhouse, which is now a museum in Grass Valley, California. This compressor was operated by a Pelton water wheel, a free source of solar energy, and provided tool air and breathing air to the two major gold mines within two miles. The Pelton wheel was—and still is—30 feet in diameter, and operated continuously for 30 years. It was one of the largest Pelton wheels ever built.

Below: From the North Star Mine guestbook of January 2, 1899. Edward A. Rix wasn't just blowing hot air when he called himself "He of the Compressed Wind." He designed the air powered locomotives used in the famous Empire gold mine just up the hill, in Grass Valley, California. He received dozens of patents for compressor parts. He co-authored a text-book on compressed air. The compressor company he founded in Oakland is still going strong.

E A Rix S. F. He of the compressed Wind

Chapter 11: The Technical Press

Introduction: The First Century of Air Car Development

Because of its many advantages as a fuel medium, compressed air has been the subject of much research and development since the middle of the 19th century. Despite its advantages, and despite a thriving air powered locomotive market that grew steadily throughout the first quarter of this century, air powered transport is no longer taught to engineers or mentioned in textbooks. As a result, many researchers and inventors who become interested in the air car question find themselves trying to reinvent the air engine, unaware of the extensive literature on the subject, of which only a small sample can be included here.

It's essential for anyone who wants to design an air car to first study the work of those who've designed air cars in the past. Fortunately, the air car faction had qualified technical people on its side for several decades, so detailed information was published in standard engineering textbooks and technical trade journals. Inventors shouldn't make the mistake of assuming that older textbooks are obsolete. The old compressed air books were written by hands-on experts who were mainly concerned with efficiency in the compression and use of air. Since the laws of physics, thermodynamics and those concerning the behavior of gasses are the same now as they were in 1887, the technical information published during the era of the compressed air locomotive is extremely useful to the modern air car inventor.

"It has been said that there is nothing new under the sun. Files of potential articles in the editorial office today contain one marked "Pneumatic Car." It will discuss current activities in the area. The January 1900 issue showed this automobile operated by compressed air and built by The American Vehicle Company, NY."

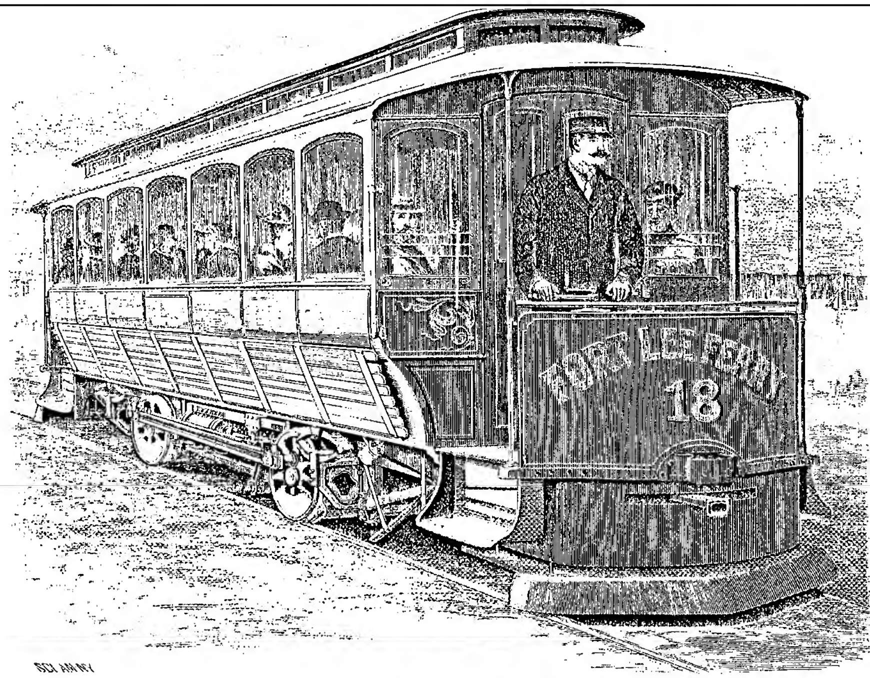
(<u>Compressed Air Magazine</u>, March 1996)

This section on the history of air cars covers only *documented* air cars: air cars that have no compressor on board and must stop to refuel from stationary compressors. Information has been published, concepts hare been patented, and claims have been made for self-fueling air car designs, but this information is vague, incomplete or speculative, and some is apparently in violation of the laws of thermodynamics. In general, the writers of the air locomotive era wrote to educate, whereas modern inventors of self-fueling air cars sometimes publicize only to tantalize. No inventor of a self-fueling air car has ever revealed his experimental results, much less the theories these results are supposed to prove. Can the engineering establishment be blamed for scientific skepticism, when the claimants refuse to put forth scientific proof? This is a call for all air car inventors to put their results into a public

forum, whether complete or not, so that the dreamers and the trained scientists can start working together toward the common goal of a non-polluting car.

When someone sets out to design any type of air car, his best background material is the documented performance data of air cars of the past that were efficient enough to be successful on the market.

This chapter is dedicated to Terry Miller, the only modern air car inventor who has fully documented and disclosed his designs and results for the education of the public.



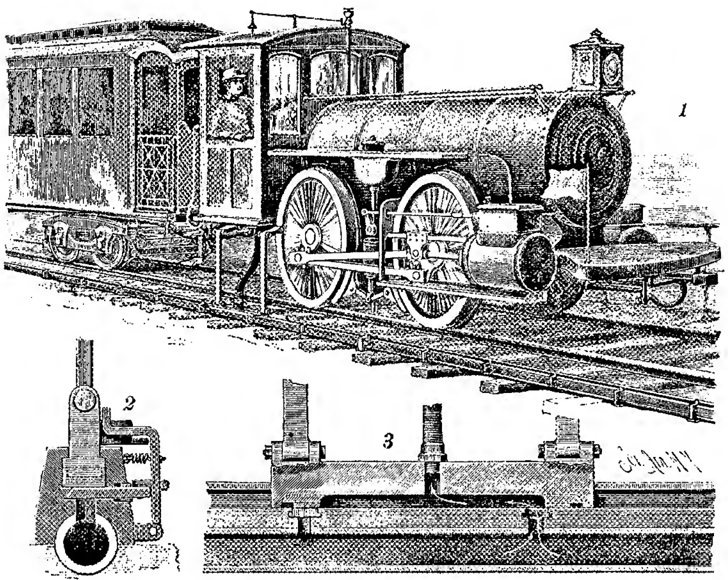
THE HARDIE COMPRESSED AIR MOTOR CAR.

The author and inventor Terry Miller, driving Terry'prototype air car at the Wichita Energy Expo, Summer 1985.

The author's air powered go kart, designed and built in ten hours.

The Pneumatic Third-Rail Locomotive, 1880s-1890s

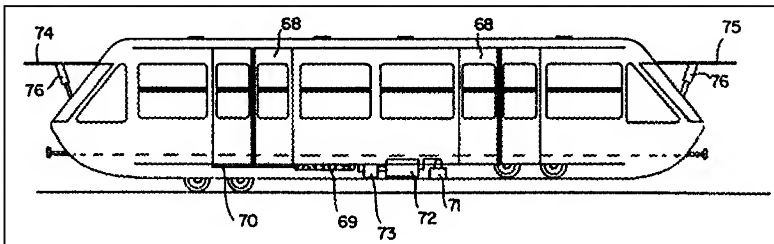
"Improved Means Of Distributing Power", <u>Scientific American</u>, 1890?, p. 250.



TOMLINSON'S APPARATUS FOR SUPPLYING COMPRESSED AIR TO LOCOMOTIVES.

A means of conveying steam or compressed along a line of road, to be delivered to a motor propelled there-on, is illustrated herewith, and forms the subject of a patent issued to Mr. Victor H. Tomlinson, of Hudson, Col. Fig. 3 is a central longitudinal sectional view of a section of the apparatus, Fig. 2 being a cross sectional view. In the upper face of the pipe or tube to which the motive agent is delivered from a central station are castings with undercut grooves, the castings being arranged end to end throughout the length of the tube, and having ports registering with ports in the tube. Within the undercut groove of the casting is a receiver with grooves to receive any proper packing, the receiver having a flexible pipe leading to the steam chest of the motor or a reservoir carried thereby. The receiver is held to the motor by upwardly extending standards, and as the receiver is forced forward by the onward movement of the motor a forward valve is opened as another at the rear is closed.

The ports in the pipe at the side of the track are controlled by valves engaged by spring-pressed levers, and a pipe leads to the steam chest of the motor, or the reservoir carried thereby, the distance between the ports being about equal to the receiver recess. The way to this recess from the pipe at the side of the track is opened by a lever as the motor moves forward, one of the valves being opened as another at the rear is closed. The economy of this system of supplying power will be readily appreciated when it is considered that steam can be generated or air compressed at a central station at a rate usually not more than two-fifths of the cost of generating such power on an independent traveling motor. The cleanliness of such a system, and the absence of noise, would also form striking advantages in favor of its adoption for the propelling of street cars, while its cost need not necessarily he higher than that of cable traction or electricity. The



The concept described in this article has not ceased to attract proponents; Oskar H. W. Coester of Brazil received U. S. Patents No. 4,587,906 & 4,658,732 for interesting improvements on such a concept in the 1980s. The above illustration is from the latter.

"The Mékarski Compressed-Air Tramway Motor,"* <u>*Engineering News*</u>*, May 24, 1890 and May 31, 1890

Among the "Reports of Consuls of the United States," for February, 1890, is one of more than usual engineering interest from Consul-General Rathbone, of Paris This is a report on the operation of the compressed-air tramway motor, on the Mékarski system, which has been in operation near Paris for over two years, and in the city of Nantes for a much longer period While we have already described this system in Engineering News of May 12, 1888, the present report is so much more complete that we give it in full, as follows:

The advantages enumerated are:

(1) The motor does not emit smoke or hot gases and is almost noiseless.

(2) A greater speed is attained than with horses where necessary.

(3) A special track or overhead appliance is unnecessary.

(4) Being very light, it can be easily handled on steep grades.

(5) Simple in form, it does not frighten horses; the machinery on the front platform is almost invisible from outside.

(6) A possible explosion of air reservoir is less dangerous than of steam or superheated water.

(7) Maintenance in repair is very simple.

(8) Only one person is necessary for manning the machinery, and he is not necessarily a skilled engineer.

(9) In crowded days or times of day the number of passenger places may be easily augmented by the addition of one or even two tenders or ordinary cars, without a motor, thus making a short train.

The principle of the system is very simple. Air is compressed to 40 or 45 atmospheres; the reservoirs of the motor are charged at this pressure; the air to be used is reduced to a pressure of 5 to 10 atmospheres, and at the same time heated to a high temperature and charged with moisture in a vessel called the heater (*vouilloitte*); from there it passes to a double expansion engine, where it acts like steam in moving a piston rod.

The running expense of this motor per kilometre has improved:

	Francs.
Charging and running	0.2079
Depreciation of machinery	0.1233
Depreciation of car	0.2360
Total	0.3076

This is 6 cents per kil., or 9½ cents per mile. Including all expenses, interest on track, etc., the cost of each car making 84 kilos. per day is 52.92 francs. The cost per day of a Paris omnibus in the same way is 106.57 francs, but the omnibus runs 90.7 kilos. and seats 50 people. Since the Mékarski tram car seats only 38 people, the proportionate expense for the same distance and the same number of people would be

$$52.92 \times \frac{90.7}{84} \times \frac{50}{38} = 75.18 \text{ francs.}$$

Therefore, the saving in this tram system is nearly 30 per cent.

The cost of the different parts of the Nogentais tramway is as follows:

	Francs.
Automobile	16,000 = $3,200
Extra or tender cars	12,000 = $2,400
Reservoirs for accumulation, containing 1,250 liters	1,250 = $ 250
Compression pumps and engines	17,500 = $3,500
Tubular boilers, 30 sq. meters surface, 327 sq.ft.	8,000 = $1,600

The weight of tram is, when empty, 7,500 kilos. (8¼ tons) and 10,300 kilos. (11-1/3 Ttons) with 40 passengers.

The co-efficient of friction, ordinarily 17 to 12% on tramways, goes occasionally down as low as 10%, or even 8%. However, by the use of sand, for which there is an arrangement, a friction of 15% can always be depended upon. The steepest grades on the line are 0.045 and 0.052. At one place the grade is 0.047 on an average for 870 ft. These steep grades are only justified by the absolute impossibility of changing the profile of the streets themselves. The minimum radius of curvature on the line is 40 meters (133 ft.) The car is designed to go round a curve of 35 meters (116 ft), however, without difficulty.

The resistance on such heavy grades, allowing for both friction and inclination, is 55 kilos. per 1000 (110 lbs. per ton). An empty motor can therefore draw up this incline—

$$\frac{7.500 \times .15}{.055} = 20{,}500 \text{ kilos.}$$

that is, 20,500 - 7,500 = 13,000 kilos. besides itself. In other words, it is capable, easily, of drawing two extra carriages of 6,000 kilos. (6½ tons) gross weight each. If the motor is full, the extra friction will admit of its drawing proportionately more—15 tons at least. This doubling or tripling the carrying capacity is very advantageous because it does not add to the number of employees working, and very little more air is consumed. Below is shown the amount of air used per unit of distance:

The reservoirs of compressed air are separated in two sections--the battery and the reserve; on leaving the station both of these are charged with a pressure of about 40 kilos. per sq. centimeter (40 atmospheres). After the complete run, that is, 12 kilos., the pressure of the battery is diminished by 26 atmospheres, and that of the reserve by 8. As each atmosphere of pressure corresponds to 2.5 kilos. of air in the battery, and to 0.8 in the reserve, the total weight of air used b $26 \times 2.5 + 8 \times .8 = 71.4$ kilos., or about 6 kilos. of air per kilo. (21 lbs. per mile). With an additional carriage in connection, it has been found that only 1.5 kilos. per kilo. (5¼ lbs. per mile) extra is required. Thus, in doubling the number of places the loss of air is raised only 25per cent.

In comparing this system with the alternative of an ordinary small-sized steam locomotive, M. Mékarski shows that in an ordinary economical locomotive 2.5 kilos (5.5 Ibs.) of coal are used per horsepower; also that the proportion of work to force generated in a compressed air motor ought to be at least 40 per cent., in order that it shall be as

economical as a steam locomotive. This state of affairs could be realized by using a stationary engine using 1 kilo. (2.2 lbs.) of coal per horse-power, an object easily attained.

To compress 1 kilo. of air in a reservoir at a pressure of 50 atmospheres, theoretically 62,400 kilogram meters are used if the compression is adiabatic, or 32,950 if it is isothermal. Practically, the operation is effected at intermediate conditions, and needs about 48,000 kilogram meters of work. The lost work in this operation may be calculated at 25 per cent. of this, or at 12,000 kilogram-meters, making the total work necessary 60,000. On the other hand, 1 kilogram. of air at a pressure of 10 atmospheres, the pressure at which the air is used, occupies a volume of 119 liters (31.44 galls.), and can furnish, with an expansion of 6 volumes, a force of 28,900 kilogram meters. Reducing this to 24,000 to allow for lost work, it is seen that the available work is $\frac{24,000}{60,000}$, or 40 per cent.

In this calculation the pressures are somewhat higher than are used in the tram-cars, for it was made in designing a larger motor; nevertheless, the proportion of pressures remains the same and the result compares exactly with the practical results shown in working the tramway at Vincennes.

It might be added that the coal used for the large stationary engine is of a very inferior quality and price to that ordinarily used in small locomotives used for the same purpose, and that they, in their turn, use more coal in comparison to their power than is used in regular railroad service. The high pressure at which the air reservoirs of the automobile are charged is the result of the necessity to compress a sufficient weight of air in a moderate compass.

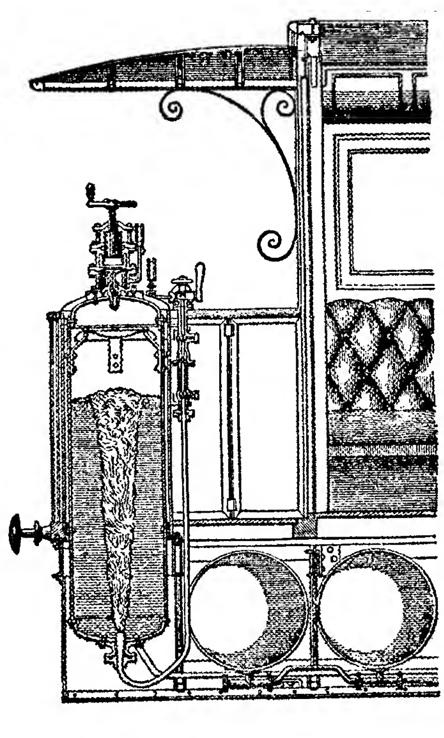


Fig. 1.—Front Platform, showing Heater.

As regards the carriage or passenger part of the car this is exactly similar to all French tram-cars, having an interior part and an upper part, or "imperial." This carriage is 8 meters (26 ft. 3 ins.) long by 2.1 meters (6 ft. 11 ins.) wide. The steps at the back are arranged to make a connection with the extra car when attached. There is also here a pipe connecting with air brakes in the last car. Parallel to the axles of the wheels of the tram are placed the air reservoirs, nine in number, divided into two groups intended to carry the compressed air. These are made of steel 12 millimeters (one-half inch) thick, and are tested for 60 atmospheres. The first of these two groups is composed of six reservoirs, having a total volume of 2,030 liters (536¼ galls.); the second group of the remaining three reservoirs, called the reserve, contains 1,066 liters (281½ galls.); the total capacity, therefore, is 3,106 liters (817¾ galls.) This volume of air at 45 atmospheres weighs 170 kilos. or 980 lbs. The battery and the battery and the reserve are made independent, in order that the reserve may always be kept at high pressure, so that an extra powerful effort may be given to the engines in case of need, even at the end of the trip. The different reservoirs of each group are connected by a

strong and permanent system of piping. Both groups send their air by pipes to the lower part of an apparatus called the heater. This apparatus is the most characteristic of the Mékarski system; and the need of some such appliance will be directly seen from the following calculation:

In considering the expansion of a gas, the proportion of the volumes before and after expansion being $\frac{V_0}{V_1}$, and the initial temperature being t_0, the temperature at the end of the expansion is

$$\frac{273+t_1}{273+t_0}=\left(\frac{V_0}{V_1}\right)^{.41}$$

In the present case $\frac{V_0}{V_1}$ being one-sixth, we find

$$\frac{273+t_1}{273+t_0}=.48.$$

If, by example, air is introduced in the cylinders at the temperature of 15° C. (59° F.), it would go out theoretically at -135° C (-211° F.). Outside of the necessity of preventing the moisture in the expanding air from freezing up the cylinder-valves, etc., we find it advantageous to have the initial temperature as high as possible. For the work done is given by the expression

$$Tm = (273+t_0)\left[29.28\left(1-\frac{P^1}{KP_0}\right)+73.3\left(1-K^{.41}\right)\right]$$

In this expression, Tm is the work effected, t_0 the initial temperature in degrees Centigrade, P^1 the resisting pressure, P_0 the initial pressure and K is the proportion $\frac{V_0}{V_1}$. Therefore, ($273 + t_0$), or, in other words the absolute temperature should be made as large as possible.

If the value for which the temperature of the escaping air is to he 15° C. (59° F.), it is found that the initial temperature should be 327° C. (620° F.), as calculated for theoretically dry air. To avoid any such inconvenience in using air at such a high temperature, and also the necessity in such a case of having some sort of a furnace, the principle in this system is to saturate the air with moisture at a much lower temperature, taking this hot water from the hot water inside the "heater". The vapor in the air during the expansion is partially condensed, and this part, giving up it latent heat to the air, acts to greatly moderate the decrease in temperature.

The heater (see Fig. 1) is in form a cylindrical reservoir placed vertically on the forward platform of the train. It also is made of steel, and contains 200 liters (53 galls.) of water under pressure and at a temperature at the outset of 155° C. (311° F.). The air passes through the water in the heater in bubbles and becomes heated, and at the same

time saturated with water. It collects here in the top part of this cylinder, which serves in the machine the pupose of a steam dome in a boiler. This part contains a curved piece of sheet-iron which forms a sort of splasher.

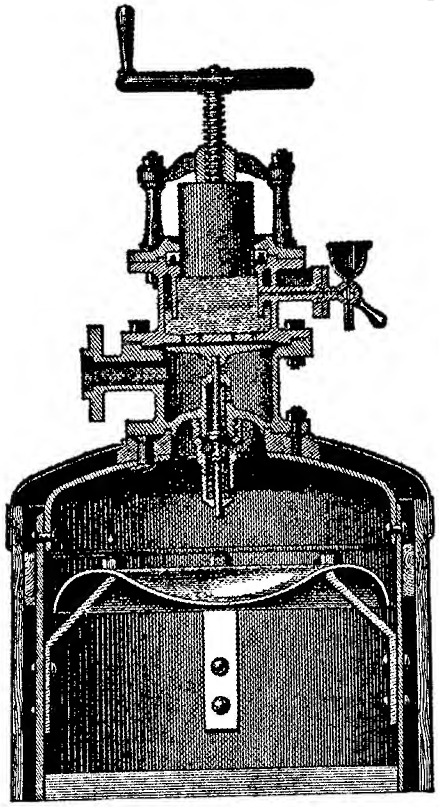


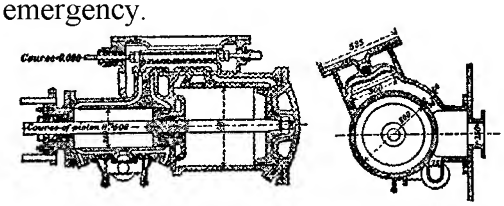
Fig. 2.—Pressure Regulator.

The regulator of the pressure ("détendeur," see Fig. 2) which the engineer maneuvers to change the pressure of the air going to the cylinders, is on top of the heater. It is a very ingenious apparatus serving to expand the air to the pressure from which it is found in the reservoirs to that at which it is to be used in the cylinders. This pressure, normally 4 or 5 atmospheres, on up grades is sometimes increased to 15, and on down grades reduced to nothing, the supply cut off, and the tram left entirely to run by gravity. This regulator is composed of two brass chambers superposed and separated by a rubber diaphragm. The first forms a hydraulic press, in which a piston descending compresses water in an annular space where a small quantity of air is confined. This cushion of air is compressed and plays the part of a spring, by which the necessary tension is easily given to the water.

The air, being heated and saturated, to pass to the cylinders goes through an orifice of the lower chamber of the regulator in which a conical valve plays. This valve is arranged in such a way that it closes by the effect of the pressure of the air in the heater. It only opens when a pressure is made on its upper face acting on the diaphragm of the little hydraulic press. It is seen that the first effect of the pressure in the hydraulic press is to open the valve and admit air. As soon as the pressure in the lower chamber gets to be as great as that in the upper, the pressures on the two sides of the diaphragm being equal, the valve closes by the pressure from below. This common pressure, which can be so easily regulated, is the pressure fed to the cylinders. This pressure, which remains automatically constant as long as the wheel moving the press is untouched, can be varied at will.

The air now passes to the cylinders, which are arranged in sets of two, each pair forming a tandem double expansion engine. The two cylinders of a set are of different diameters and are cast in one piece. The rod of the two pistons passes through the cylinder head in a spring metallic stuffing-box. The air is admitted to both cylinders in succession by the means of the same compound slide-valve. The admission to the smaller cylinder is cut off at about two-thirds the stroke. This air is now passed into the larger cylinder, whose volume is four times larger than the first. The total proportion of expansion, therefore, is about 6 volumes. Such an expansion cannot be produced with the steam in locomotives, especially where great promptitude is required. Both factors governing the tractive power can be changed--the cut-off, and the pressure of air--and consequently this system is one that can be most perfectly controlled. Since, however, from this large

expansion it might result that with an initial pressure and cut-off the expansion would be to a pressure less than 1 atmosphere, and a negative work would ensue, there has been placed at the lower part of the cylinder an air-valve allowing outside air to enter in such an emergency.



LONGITUDINAL SECTION. CROSS SECTION.

Figs. 3 and 4.—Sections of Cylinder.

Figs. 3, 4 show a cylinder rather larger than the one in use on this tram-way, designed for a full-sized locomotive. It, however, shows the proper proportion and arrangement of the parts. The speed, so easily varied, can be made as much as 65 kilos. (40 miles) an hour if necessary. The legal limit of speed on the tram-way is 20 kilos. (12½ miles).

The arrangement of the machine, in which the space inside the wheels and under the car is entirely taken up by the reservoirs, obliges the cylinders and their dependent parts to be placed outside. Their protection, however is insured by a sheet-iron boxing, which, with its closed doors, conceals everything under the car. In order that no difficulty in cold weather from the collecting and freezing of the moisture in the air may take place, the air is led from the exhaust valves of the cylinder by a pipe out of the box and under the car. So far the coldest weather has not had any disagreeable result in any part of the machinery.

The engineer is placed on the front platform of the tram, which is railed off from the public, and manages the regulator. Two manometers are placed on top of the heater, and indicate the pressures in the battery and the reserve. A third manometer gives him the pressure in the regulator and the cylinders. All the motions of maneuvering the machine are extremely simple: there is a lever to change the action of the slide-valve, thus giving more or less cut-off or changing the direction of the motion; there is a lever to apply the air brakes; another to cut off the supply of air to the cylinders, and a small cylinder in which, when the piston is pressed down, the escaping air sounds a horn.

The two pairs of wheels are coupled by a connecting rod; thus both act as drivers, and the whole weight of the car is made use of in propelling itself. The axles being only 1.6 meters (5 ft. 3¼ ins.) apart, they allow the car to go around the shortest curves without difficulty.

The tram, when charged with air, could make on an ordinary grading a run of over 20 kilos. (12½ miles) without recharging, but on this track only 14 kilos. (9 miles) can be made,on on account of the heavy grades and the unusual obstructions in the way of dirt, etc. The mean consumption of air on this line is about 10 kilos. per kilo. (35 lbs. per mile) where the grade is the heaviest; where the grade is only 0.02 only 7 kilos. per kilo. (24 lbs. per mile) are necessary.

The machinery and apparatus for compressing the air is in two sections at two different stations, the larger at La Maltournée, and the other at Vincennes. The station at La Maltournée has—

Two tubular boilers of 60 meters (653½ sq. ft.) heating surface apiece in the boiler house.

In the engine room, four 35 horse-power steam-engines, each working a large air compressor.

A reservoir room containing twelve reservoirs of air at 45 atmospheres of 1,250 liters (330.2 galls.) capacity and intended to contain the air compressed by the pumps in the intervals between the charging of the cars.

Reservoirs of water and a feeding pump for the boilers.

A workshop containing an engine, lathes, punching machines, blacksmith's shop, etc.

An electric dynamo (Gerard) for incandescent lighting.

A charging room for the tram-cars.

Stables for the rolling stock.

Offices for employees, ticket office, waiting-room, etc.

Coal yards and yards for road materials.

The operation of charging the tram reservoirs is made in a special room called the charging-room. The reservoirs should hold, before the start, 3,106 liters of air, and the heater 200 liters of water at a temperature of 155° C. The air and the steam which heats the water are brought to the charging-room by pipes--copper for the steam and iron for the air. These pipes end in orifices provided with screw cocks. The water in the heater is heated by passing the steam from the steam-pipe through it, and it is only refilled with water when the heater is emptied for repairs. For the operation of charging, the cars are brought opposite the cocks, and by means of connecting pipes the cocks are put in connection with corresponding cocks in the car. The duration of charging is about fifteen minutes.

It has been found possible, however, in the case of prolonged runs to have air pipes brought to the side of the track, and a partial refilling of the reservoirs effected while tickets are being taken, etc.; this takes only about three minutes.

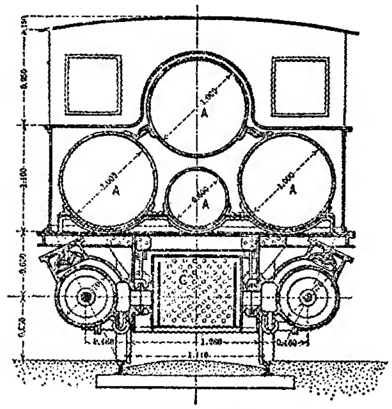
There are two parts of the Nogentais tramway that might be called the main line and the branch; main line, 9,580 meters (31,432 ft.); branch line, 2,108 meters (9,916 ft.); total length, 11,688 meters (38,848 ft.)

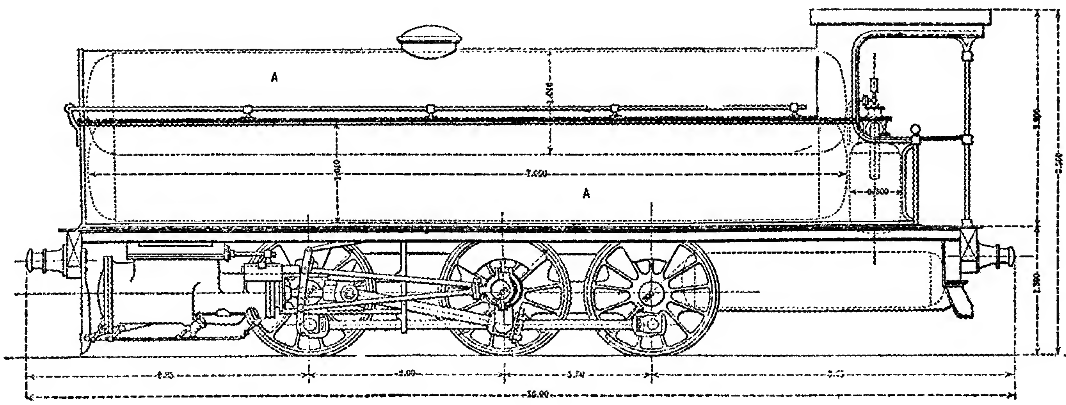
In a supplemental report Mr. Rathbone speaks of the application of this system to locomotives, as illustrated in Fig. 5. This engine was designed for use on a metropolitan railway, either in a tunnel or elevated, where steam would be objectionable. He says:

"M. Mékarski shows that with a charged pressure of 50 atmospheres air locomotives might be constructed of an external form similar somewhat to steam locomotives, without tenders or smoke stacks. The air reservoirs occupy on the frame the place of the boiler, without obstructing the engineer's view. He has designed, with this idea, the two types of locomotive given in the plate, showing the side elevations of each and a transverse section. The first type in working order weighs 40,000 kilos. (44 tons). It carries three large cylinders charged each with compressed air. The second model is composed of two smaller carriages coupled back to back like a locomotive to its tender. The two form a locomotive of 50,000 kilos. (55 tons).

"The 55-ton locomotive is designed with a view to develop a tractive power of 6,000 kilograms (13,228 Ibs.) and to run around curves of 150 meters (492 ft.). It is composed of two separate machines mounted on two coupled pairs of driving-wheels each The reservoirs of compressed air are mounted on the two trucks,which are so arranged that a central cab, where the engineer is placed, is formed by the joined ends. The view from this cab is in no way obstructed by the reservoirs in either direction, and they are entirely hidden under a covering of sheet-iron.

“The total length of the track from end to end, including the buffers is 14.4meters (47 ft. 3 ins.); the greatest width is 3.2 meters (10 ft. 6 ins.), and greatest height above rails 1.3 meters (4 ft. 3 ins.), The diameters of the cylinders are, respectively, 0.26 meter (10¼ ins.) and 0.5 meter (19-5/8 ins); the common stroke is half a meter (20 ins.) Each of the four reservoirs is 5.2 meters (17 ft. 1 in.) long. Three of them have an internal diameter of one meter (39-3/8 ins.); the fourth, smaller, is only 0.6 meter (23-5/8 ins.) in diameter. The





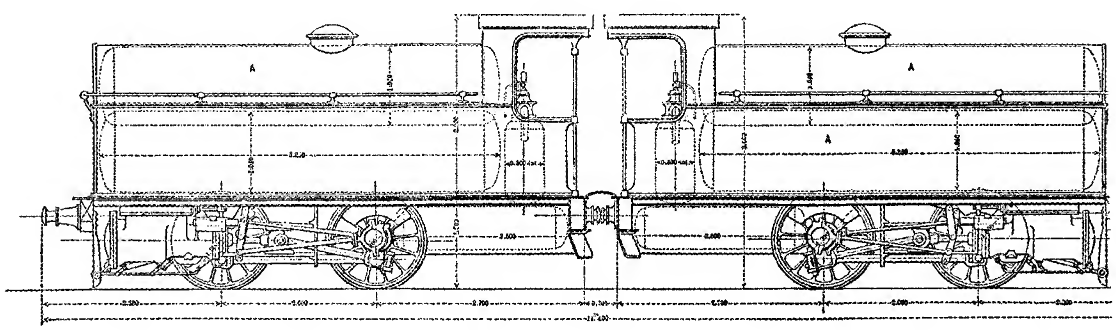


Fig. 5.—Forty- and Fifty-ton Locomotives on the Compressed-Air System, designed by M. Mékarski for the City of Paris.

reservoirs are made of soft steel, 20 millimeters (¾ in.) thick for the large, and 12 millimeters(½ in.) for the smaller one. The total capacity of one battery is 13 cubic meters (460 cu. ft.); the weight of air compressed in them would be 800 kilograms (1,764 lbs.), or a total of 1,600 kilos (3,528 lbs.) Each battery weighs about 10,500 kilos (11½ tons).

“There is a heater and a regulator on each part of the locomotive, but they are so arranged that by maneuvering one of them all the cylinders of both machines will be similarly affected. Besides the hot water in the two heaters proper, there is an extra supply of hot water in two reservoirs under each part of the cab--four reservoirs in all which

communicate with the heaters. The total capacity of hot water in each machine would, therefore, be l,000 kilos. (2,205 lbs.)

"The air in this machine, after being used, passes through an arrangement which might be called a condenser. This is used in order that no moisture, even in minute quantity might be deposited in the tunnels. It acts simply to connect the moisture in the exhaust air, and is in form similar to a tubular condenser for a steam engine.

"There is little to be said of the 44 ton machine, after having the preceding description, since it has very much the same characteristics. It is formed of a single frame mounted on three pairs of driving-wheels, all coupled. The reservoirs are of the same diameter as in the 55 ton type, and are similarly placed, only varying in their length. It might be added that, no fireman being needed for these locomotives, a great saving in wages is effected, but this is nearly made up for in the extra labor, capital, and wear incurred in having the extra stationary plant."

Mr. H. A. Shackelford, Consul at Nantes, adds as follows concerning the operations of the line in that city: The maximum grades in the line in Nantes are about 25 ft. per mile, but present no difficulties in operation. The cars used are clumsy and weigh twice as much as American cars. The cost of running a car, for a daily run of 60 miles, is as follows:--for coal and oil, $1.20; wages for operator and conductor (New York prices) $3 to $3.50; repairs to cars, $1.80; total $6.50 per day, or 10 to 11 cts. per mile.

Other Outcroppings of Mékarski's Air Car

"Compressed Air Motors at Berne," Street Railway Journal, Vol. ix, No.4, 1893:

In Engineering some interesting particulars were recently given of the Mékarski compressed air railway, at Berne, Switzerland, one of the few street railways in Europe operated by compressed air. The line at Berne is two miles in length, and the rails, which weigh sixty-six pounds to the yard, rest on gravel foundation or on concrete where the soil is loose. Seven motor cars are used, running on a ten minute headway, and the average speed, including stoppages, is six miles per hour. Each car has a carrying capacity of twenty-eight passengers. The fares are at the rate of two cents per mile, and gross earnings in 1891 amounted to 21.4 cents per car mile, of which sum the working expenses amounted to 83 per cent. The cost of motive power per car mile is given as follows: Wages, 5.86 cents; power station (water power), 3.72 cents; renewals of plant and motor, 1.86 cents; sundries, .3 cent; total, 11.74 cents. The maximum pressure used is 440 lbs. per square inch.

Engineering News, December 27, 1894:

Street railway motor cars operated by compressed air on a modification of the well-known Mékarski system, have been in service at Westfield, Mass., for several months, experiments having been made with a view to materially reducing the weight of the car without reducing its efficiency, and the desired results promise to be obtained. As a result of the practical experiments the American Compressed Air Motor Co. has been incorporated in New Jersey, with a capital stock of $250,000. Among the incorporators

are John Fritz, of Behlehem, Pa.; J. F. Lewis, of Chicago, Ill.; Addison G. Rand, of New York City, and E. W. Dickeman, of Westfield, Mass.

"Compressed Air Motors," Carl Snyder, Harper's Weekly, December 5, 1896:

For the last three months, on the 125th Street surface line in New York City, two new cars have been in operation that offer at novelty in the way of street traction. They run without visible means of propulsion; there is neither overhead trolley cable nor conduit; they are very near to noiseless, they run smoothly, and start and stop without jerk or jar. These cars alternate with those propelled by cable, and, save in the smoothness of their operation, there is outwardly nothing to announce that they are unique. They have thus far covered 12,000 miles and carried some 75,000 passengers, and this not so much without accident as without incident. They are a long stride toward the dream of the street-railway manager—an independent self-contained motor—and that they are successful means much. If the claims of economy are substantial it is an allowable surmise that this is the traction force of the future in large cities if not in small.

"...if a given quantity of compressed air costs a dollar to gererate, the further expenditure of ten cents in reheating will double its power to do work."

The new motors represent the latest phase of development in a very wonderful new power which has been rapidly coming into use in the last ten or fifteen years. That is compressed air. The remarkable powers of this force have been largely lost sight of in our modern flood of marvels. If, a hundred years ago, Franklin had made an announcement of a way to bottle up the ambient atmosphere in steel flasks or flasks of any sort, and to tuck these in obscure corners, and use the power resident in them for many and divers conveniences, there is hardly room for doubt that his discovery would have been regarded in that day every whit as extraordinary as his feat of drawing lightning from the clouds. And there are those of competent judgment who believe that if a tithe of the inventive and mechanical genius that has been employed in the development of electricity had been diverted to the perfection of appliances for the use of compressed air, the present relation of these two novel aids of industry would be very different, if not reversed. But electricity was mantled with the glamour of the unknown; for a long time there seemed no limit to its capabilities; it was being applied everywhere and in the most surprising variety of ways; and in the furor it created, compressed air found little favor beside its more its brilliant rival.

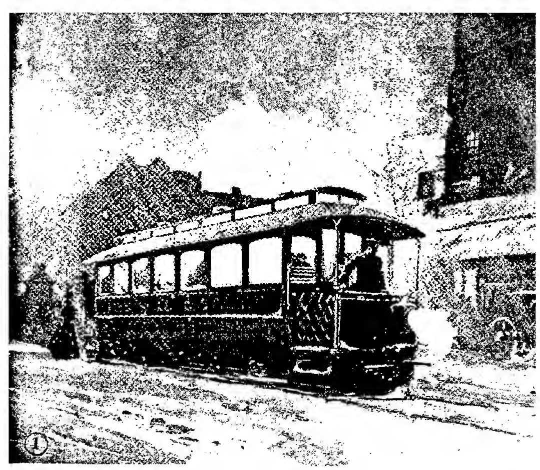


Fig. 1—Car using the Hardie Compessed Air Motor on 125th Street, New York City.

Of recent years, however, the limitations of electricity have become more clearly defined, and in the mean while compressed air has gained a hearing. There are few, perhaps. outside of those who follow the technical journals, who are aware of the immense

progress that has of late been made in the employment of this new power, and the astonishing multiplicity of uses to which it is now put.

The Westinghouse air brake, and the compressed-air drill that is to be seen almost any day making excavations for buildings and the like, have long ceased to be regarded as novelties. But it is different when we learn that this same force is now used to start cars, and even to run them, and that this same air-drill, working in the mine, has literally added hundreds of millions to the available mineral wealth of the world. The enormous increase in the production of gold, as well as of silver, coal and iron, copper, and other metals, has in no small part been due to this convenient tool. Further, it has been the principal agent in the construction of Chicago's great drainage canal, in many respects one of the most wonderful enterprises of the day.

Then again, we are all of us aware of the use of compressed air in the Zalinski dynamite gun, which is able to hurl a charge of explosive a mile and a half, sufficient to convert a whole regiment into unrecognizable pulp. It is another matter to learn of this same force cleaning carpets, dusting cushions, and painting cars and barns. And as we go a little further, we find this Protean force operating block signals on our railroads, and steering ships, running clocks, and furnishing cold air for refrigerators, loading guns and handling projectiles on our men-of-war, propelling sewing-machines, doing all sorts of hoisting-work, driving lathes and printing-presses, copying letters, and running summer fans. In Australia it is shearing sheep; in Kansas City beeves are slaughtered and the meat dressed mainly with compressed air. It is an excellent pump, especially for deep wells, and in particular for chemicals. With the same power you may dump a whole train of coal or dirt cars by the pressure of your thumb. It is carving beautiful statuary, and employed in all sorts of stone-work; it makes a good dredge; it raises and lowers railroad gates; it is a valuable agent in the sugar-refinery and in the making of asphalt and rubber, and still again in the delicate manufacture of fine silk. In the coal-mines it is running locomotives, bringing oxygen and life to the exhausted operative, and banishing the fear of deadly explosions. In England a hundred and fifty miles of pneumatic tubing facilitates the rapid transfer of mails, and the same system is in use in Philadelphia, and just recently between New York and Brooklyn. In England, again, employed in the dry docks, compressed air is made to lift huge vessels out of the water as if they were toys, and in the same way it will shortly be introduced on the Erie Canal in working the new quick-action high-lift locks. It is a good fire-extinguisher, and an excellent hoist for grain. It is used by the physician and surgeon in many delicate operations. In the railroad shops of Jersey City and many other points it is everywhere running machinery, lifting huge loads, riveting bolts, driving hammers, sand-papering cars. In Paris, under the famous Popp system, where it has had its widest application, it is employed in almost every conceivable variety of work.

Now that this new power has, so to speak, found its feet, it would be difficult to set limits upon the vast variety of uses to which, in the future, it will be put. It forms the basis of the gigantic project of a great ship-canal from the Great Lakes to the sea, described in these pages a year or more ago, which will be equipped with locks capable of raising an ocean liner to the height of Niagara with the same ease as a clumsy canal barge is now lifted the height of a bean-pole, and with much more rapidity. The bicycle tire, the pneumatic cushion and pillow and horse collar, are but a beginning of its use in this direction, and it seems now the most convenient power for the automobile cart. And when

it is generated in large central stations, and distributed over the city in the same way that gas and water and electricity are now distributed, you may expect, madam, that it will clean house for you—beat your carpets and clean your walls--and take a general hand in your household affairs. It will pick you up and set you down from floor to floor. It will be waiting for you at your door, and whisk you to the shopping districts. It may treadle the sewing-machine, agitate the dish-washer and smash your costliest china with all the dexterity and *sang-froid* of your most accomplished handmaiden. All this and much more it may do, if we are to believe some of those who are given to peering into the to-morrow of things. These tell us that even now compressed air is an equal-footed rival of electricity, and that while the latter has been thrusting the steam-engine from the field, compressed air has entered the lists against this latest knight of industry.

In view of all these things, its multiplied uses in the present, and the large possibilities of its future, the wonder of it all now seems that compressed air should not have come in long ago. It is not new, any more than electricity is new. In a sketch of its history in an interesting little periodical, Compressed Air, published in New York City, the earliest notable use of this power is set down to the construction of the Mount Cenis tunnel. It was first employed on a large scale in this country in the building of the Hoosac tunnel, along about 1866, and from this time its advancement has been steady and sure. But it has been, apparently, the Cinderella of the mechanical arts. It made its appearance in an age given over to a sort of electrical mania, and there seemed no godmother genius like Tesla or Edison to bring the golden slipper to its neglected hearth.

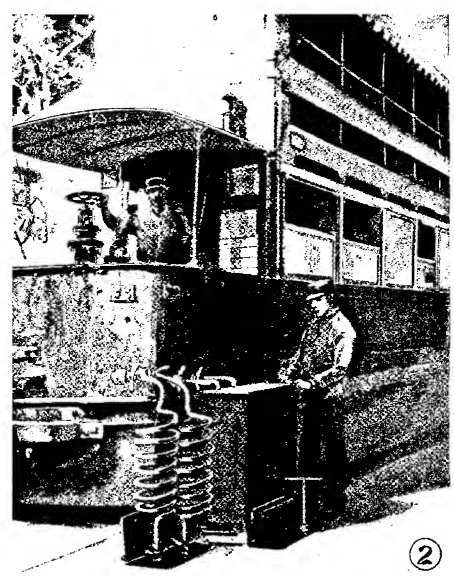


Fig. 2.—The Mékarski Compressed Air System used in Paris—recharging *en route.*

Three notable steps of advance wrought a striking change in this order of affairs. When compressed air was first tried, it was found that the loss of power was enormous. It was difficult to store, for the air leaked rapidly away; it was expensive to generate, and there were thermo-dynamic difficulties in its use without number. When a thousand cubic feet of air is jammed into the space of one, a large amount of heat is developed, and in order to store and use the air this heat must in some way be drawn off. Similarly, air at high pressure, when released, cools rapidly. The result, if there be a sufficient moisture, is freezing and clogging. For a long time it was thought these difficulties were largely insuperable.

Now, however, these very difficulties are turned to a profit—to such excellent profit, indeed, as to afford an apparent paradox. It seems idle to assert that it is possible to get as much power out of a machine as you put into it—this means a frictionless and wasteless mechanism. And yet a very near approach to just this condition seems to have been made in the case of compressed air. This is due to the development of the reheating process. Lest the reader be not familiar with the technique of the subject, it may not be idle to explain its broader features. In the process of

compression the air is sucked into a piston, and then rammed into a reservoir surrounded by a water jacket, the latter drawing off the heat generated in the compression. The machine which does this work is a beautiful affair of what is known as the four-stage type. That is to say, the air is first driven up to about eighty pounds pressure and cooled; then turned into a second cylinder, where it is compressed still further, then cooled again; and so on up to the desired point. Thus even at two or three thousand pounds pressure to the square inch the air within the reservoir remains at somewhere near the temperature of the outside atmosphere. But if the air be used in this condition, not only will a large share of the power employed in compression be lost, but it will, as already noted, have a tendency to freeze everything within reach. If, however, as it is released, it is passed through a heater or is shot through superheated hot water it will, under the well-known properties of air, enormously expand. In actual practice it has been found possible to add, by reheating, one horse-power to each horse-power developed by compression, at one-eighth or one-tenth the original cost of the latter. That is to say, if a given quantity of compressed air costs a dollar to generate, the further expenditure of ten cents in reheating will double its power to do work. Theoretically the total efficiency thus obtained is actually greater than if the same amount of coal had been burned in an ordinary steam-engine and the power thus generated used direct. In practical use it is slightly less.

With the reheating method came a marked improvement in compressing apparatus, in which advance, it is to be noted, the United States has taken the lead. There yet remained a third problem, the same that has baffled the electrician—the question of storage. It was found that air at high pressure is much more penetrating, for example, than steam. Now, however, storage reservoirs have been devised in which the loss from leakage is next to nothing. These are known as Mannesmann tubes, and are simply large, seamless, rolled flasks of mild steel, with but a single vent. These are of high tensile strength. and may be drawn to hold air at very high pressure. With these it is possible to reach a large amount of stored-up energy in a very small space, and without danger, for if these tubes were to burst they would not fly in pieces, but would simply rip, like a leather bag, and beyond a swift rush of air and a loud report there would be no hazard to life. With low cost of generation, economy of expenditure in use, and perfect storage, it remained only to develop the special appliances for its immediate application to give compressed air its present wide range. In particular did this advance make possible its use as a traction agent. The first to experiment in this field were the French. The surface cars to be seen in New York City are by no means the first of their kind. They represent simply an improvement of the well-known Mekarski system of Paris. The latter has been in use in the French capital for something like ten rears, and a number

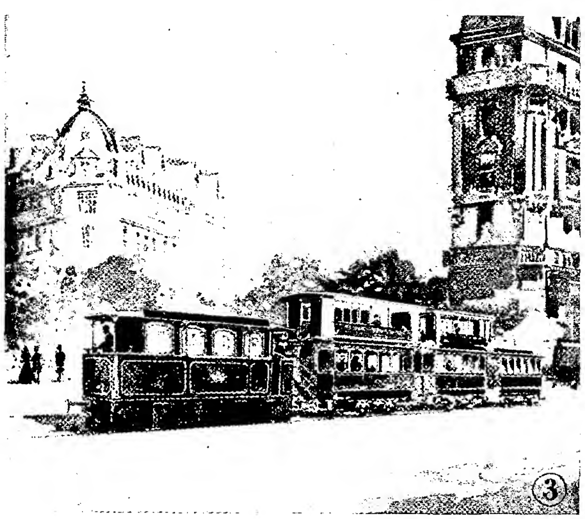


Fig. 3.—Motor and Train in Paris (Mékarski System).

of different attempts have been made from time to time to introduce it in this country. The requirements of a service for the narrow and crowded thoroughfares of a city like New York, however, seemed too great for the French system to meet. It was not economical, it was heavy and clumsy, and not feasible in other ways. The Hardie system—that in use in New York City—seems to have overcome these difficulties, and, furthermore, to be able to cope with the peculiar and perplexing conditions which obtain in the congested portions of a large city where the overhead trolley is not allowed.

The cars are identical in appearance, both inside and out, with the type used on the cable or trolley roads, and the motive apparatus is completely hidden from view. It is located entirely beneath the seats and the body of the car, and is controlled by a mechanism that out-wardly does not differ from that for the control of the trolley. As the car starts, there is some slight hissing noise, and that is all. The ease with which it is started and stopped does away with the exasperating jerkiness of the cable; and aside from this, the system seems much safer, from the quickness with which the car may be brought to a standstill. In cases of prime necessity the whole force of the compressed air which the car carries may be thrown upon the wheels, and a dead stop from full speed effected in a few feet. The immediate operation would no doubt slightly dislocate the occupants of the car, but it would be a departure from the system of wholesale depopulation and dismemberment which seems the special mission of the trolley. Like the latter, the speed of the motor is variable within wide limits, and much faster runs may be made at night, after the theatre, than is possible with the cable.


Fig. 4.—Compressed Air Locomotive to be operated on the Elevated Railroad in New York City.

The mechanical features of the Hardie motor are exceedingly simple. An apparatus substantially identical with that of the steam-locomotive is supplied with compressed air, instead of steam, from tubes extending under the car seats. These tubes or cylinders are charged at two thousand pounds pressure, but when used the air is passed through a reducing valve, bringing the pressure to one hundred and thirty pounds. The reheating is effected by forcing the air, before its entrance to the valves of the driving-gear, through a chest of superheated water. In its passage through the latter the air is not only enormously expanded, but is converted into a sort of vapor, which, it is claimed, gives a peculiarly high efficiency. In all about fifty-one cubic feet of air is stored in the steel reservoirs, affording sufficient power to run the car fifteen or eighteen miles, including stops. The time occupied in recharging the cars with air and hot water is not more than a minute, so that there is practically no delay. The motor mechanism itself consists of two simple. link-motion reciprocating engines, which do not differ materially from ordinary steam-engines in their features, save in their use of air. By ingenious device it is possible to start the motor at any point, and there is thus no chance for stoppage over a "dead-centre." It is to be noted that this ability to start promptly under all conditions is a feature

the lack of which has been one of the principal causes of failure of air-motors heretofore tried. Still another unique device is that by which a surcharge of air is admitted to the valves in order to accelerate the start, this pressure being shut off when the car gains its full speed. The manipulation of the whole mechanism is exceedingly simple, requiring no more skill than that of the ordinary trolley. The cars move in either direction with equal facility, and are under such perfect control that it is possible to start and stop them within a space of two inches. The same lever that re leases the brakes operates the starting-gear, and, similarly, brakes are applied and the air cut off with a single motion of the wrist. As I am confining myself entirely to the favorable points of the new motor, it may be added that further claim is made for the Hardie motor that it is the cheapest of all systems in point of first cost, since it requires no subterranean or overhead construction, and can be introduced on any track. Each car being independent and carrying its own motive power, no derangement of machinery at the central station or of the "feeder"—that is, of cable or trolley—can affect the whole line. Electrical storms are, of course, no danger, and there are no cables to strand and to afford the reporters for the morning newspapers material for exciting tales of running-away cars. There is no dissipation of energy, as in the case of steam, trolley, or cable, since practically only such power is taken as is actually used. The smoothness of operation represents a further economy, alike of temper and profanity, so that I doubt not the ingenious promoter will hardly fail to represent them as an agency for the moral regeneration of the community.

There remains the single factor of economy of operation . Diligent inquiry upon this point failed to bring forth any really illuminative facts; probably the latter do not exist. It is claimed that compressed air for traction is less than half as expensive as the cable; and there is a further gain in fixed charges, since the cost of insulation is immensely less than in that of the cable of the underground trolley. This can only be demonstrated by actual experiment, such as is now being made in New York. Aside from the trial on the 125th Street line, the same company has now under construction a compressed-air locomotive which will be employed to draw a train of five cars on the Manhattan Elevated Railroad between Rector and 58th Streets. Still further, besides the Hardie system, the Metropolitan Railroad has on trial yet another compressed air motor, the invention of W. J. Knight and Joseph H. Hoadley. Three cars of the latter construction are now in use on the Lenox Avenue line. but of their capability, as of their special points of construction, the inventors do not as yet care to speak.

The detail of the development of compressed air here given is necessarily but a sketch, but even this will disclose that much more than a beginning has been made. The general use of the new power will come only with the advent of large central distributing stations, from which it can be had as freely as is gas or water now. While in a sense it is a rival of electricity, yet it is not impossible that it will soon become a yokemate rather. The alternating electrical current may be employed to transmit cheap power long distances, as from Niagara and the Pennsylvania culm-banks, and this power converted into compressed air at the point of consumption—electricity being probably the best agent for distance transmission, and compressed air the most mobile form of power for immediate use. Even this is mere conjecture, however, since there is at least one engineering genius—a man of remarkable achievement, at that—who has distinctly in view the compression of air at great water-powers like Niagara, conveyance by pipe-lines, at enormous pressure, so far

as New York or Philadelphia, and delivery at prices with which electricity cannot compete. But whether as yokemates or rivals, it must be clear to the dullest imagination that present conditions are but a stage, and that we are but on a threshold of the day when these two forces, harnessed and trained, will, from their cheapness and availability, and in their infinite application, lift a considerable share of the burden of physical toil from the shoulders of the race.

The Hardie Compressed Air Locomotive, 1892-1900

"Compressed Air for City and Suburban Traction," Herman Haupt, Journal of the Franklin Institute, January. 1897, p. 13.

Although a considerable amount of compressed air literature has been given to the public during the last two years, there is still a want of information as to the efficiency and economy of air motors as compared with cable, electric and other systems, and statements are continually published in the columns of the daily press that exhibit ignorance of scientific facts and apprehension of imaginary dangers.

Compressed air motors have been in successful operation in France for many years, and they are now rapidly establishing themselves in public favor in the United States. They have been constructed and tested at Rome, New York, continuously for two years, in all conditions of weather, and have given satisfaction even at temperatures below zero. Several motors are now, and have been, running for some months on the One-hundred-and-twenty-fifth Street Railway, in the city of New York, in daily service, without having lost a trip and with great satisfaction to the public.

The attention of the writer was first directed to the use of compressed air for city service in 1879, when he was called upon to examine, test and report upon several motors that had been constructed under the supervision of Robert Hardie, and allowed to be run on a portion of the Second Avenue Surface Railway, at Harlem, in New York. These motors were tested for several weeks, and the results were entirely satisfactory; but all attempts to secure their introduction proved fruitless. There was so strong a prejudice against them, that the president of one of the city railroads in Philadelphia declared that he would not have such a motor on his road if it saved the whole cost of horse-power; that it would frighten every team on the street to see a car running without horses, and the company would be perpetually annoyed by lawsuits. Explanations proved useless, and efforts were abandoned.

After the far more objectionable and expensive cable and trolley systems had been introduced and had demonstrated that a car could be run without horses and without frightening teams, the writer renewed efforts to educate the public, and especially the profession, in regard to the superior merits of compressed air. A book was published,* giving a description and comparative cost of all the systems known or used for city

This was followed by a number of monographs on special points, and finally resulted in the formation of a syndicate to raise capital and organize a company under the title of the General Compressed Air Company. The services of Mr. Robert Hardie were secured as engineer, and a motor constructed at the Rome Locomotive Works, which proved

* Street Railways Motors, Herman Haupt, London: Henty Carey Baird & Co., 1893.

entirely successful from the start, and has been examined, tested and favorably reported upon by engineers, experts and scientists from all parts of the United States without exception.

Very erroneous opinions have been and are yet entertained in regard to the power lost in compressing air, the frost produced in expansion, the danger of explosion, the reheating of dry and moist air, the cost of plant, the necessity for frequent renewals of air supply, the possible length of run, the loss by transmission of air to distant points, and other matters connected with the practical application of air as a motor.power.

That the subject of air motors may be intelligibly presented, it is necessary to state briefly some of the properties of air and the laws which govern its compression, expansion and distribution, also such of the properties of steam as enter into the consideration of the questions at issue.

Physical Properties of Air and Steam.

Air at a temperature of 32° F. requires 12.433 cubic feet to weigh 1 pound; at ordinary temperature about 13 feet.

The weight of steam at 212° is 26.4 cubic feet to the pound, or approximately, for rough calculation, 26 feet. *Specific heat*, or capacity for heat, varies with different substances, and it is a very important element in calculations in thermodynamics. Water, having the greatest capacity for heat, that is, having a capacity to retain the greatest number of heat units per pound, has been taken as the unit of specific heat. On this standard, the specific heat of air is .2377, or approximately .24.

The specific heat of steam is .475, or approximately .48, or double the specific heat of air. In other words, steam is half as heavy as air, but has double the capacity per pound for retaining heat.

If air be suddenly compressed to one-half its volume, the temperature will be raised 116° and if suddenly expanded to double its volume the temperature will be reduced to the same extent.

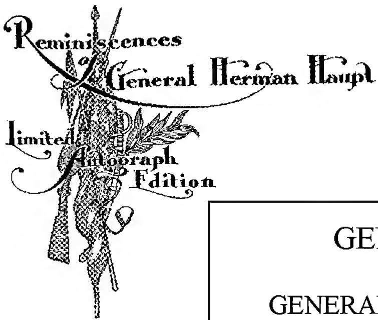
Under high pressure a given increase of pressure will develop much less heat than at low pressure. For example, a given volume of air at atmospheric pressure, condensed suddenly to one-half by an increase of pressure of 15 pounds, would develop 116° of heat, while under a pressure of 25 atmospheres an increase of pressure of 1 atmosphere would raise the temperature only 16.7°

A thermal unit, or unit of heat, is the quantity of heat that will raise the temperature of 1 pound of water 1°, and a thermal unit is the equivalent in work of 772 pounds raised 1 foot.

A horse-power is 33,000 pounds raised 1 foot in 1 minute.

Isothermal compression is compression without evolution of heat. If this were attainable in practice, as much energy could be utilized in the expansion of air as was expended in compression.

Adiabatic compression is compression with evolution of heat. By compression and intermediate cooling it is claimed that 80 per cent. efficiency may be obtained. Under old systems of compression the loss has been conceded to be 50 per cent. The capacity of air for holding moisture is affected by volume and temperature, but not by density. A cubic foot of air will hold no more water at the same temperature under 133 atmospheres than



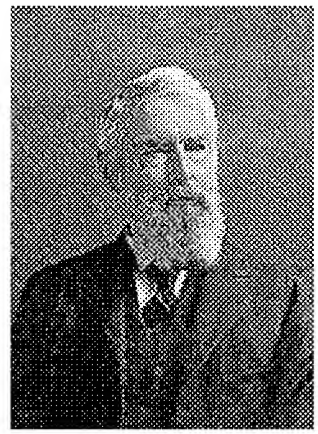
GENERAL HERMAN HAUPT.

GENERAL HAUPT, now in his 85th year and the active head of an important manufacturing enterprise in the United States, is one of the most interesting, as he certainly is one of the most remarkable, figures in our history.

Few men have participated in so much that has contributed to the growth and grandeur of our country, yet how little the world knows of his career, how reluctant the trumpeters have been to herald his achievements !

A designer and builder of roads and bridges; a constructor of railroads and tunnels; a professor and author; an inventor and master mechanic; a military strategist and civil counsellor; a railway manager and canal engineer; a manufacturer and organizer of great enterprises; a military and civil engineer, still up-to-date and a leader of progress, he links the old with the new, the slow and sleepy past with the swift and dashing present in a way that is entirely exceptional.

He was born in Philadelphia on March 26, 1817. His father, Jacob Haupt, died in 1828, leaving a widow and six children.



Who was General Herman Haupt?

REMINISCENCES

OF

GENERAL HERMAN HAUPT

Director, Chief Engineer and General Superintendent of the Pennsylvania Railroad
Contractor and Chief Engineer for the Hoosac Tunnel
Chief of the Bureau of United States Military Railroads in the Civil War
Chief Engineer of the Tidewater Pipeline
General Manager of the Richmond & Danville and Northern Pacific Railroads
President American Air Power Company
Etc Etc

GIVING

HITHERTO UNPUBLISHED OFFICIAL ORDERS,

PERSONAL NARRATIVES OF IMPORTANT MILITARY OPERATIONS,

AND

INTERVIEWS WITH PRESIDENT LINCOLN, SECRETARY STANTON, GENERAL-IN-CHIEF HALLECK, AND WITH GENERALS McDOWELL, McCLELLAN, MEADE, HANCOCK, BURNSIDE, AND OTHERS IN COMMAND OF THE ARMIES IN THE FIELD, AND HIS IMPRESSIONS OF THESE MEN

[WRITTEN BY HIMSELF]

WITH NOTES AND A PERSONAL SKETCH BY
FRANK ABIAL FLOWER

Illustrated from Photographs of Actual Operations in the Field

1901

Signed Herman Haupt

IN JULY, 1901.

under 1; consequently, when this air is expanded to original tension, 1 cubic foot will contain only 1/133 part of the moisture that it had originally and should be too dry to form a deposit of ice at the exhaust even if not reheated. Only low pressures can contain sufficient vapor to cause trouble; but as air should always be reheated, for reasons that will be explained, the difficulty from frost is purely imaginary.

Absolute or theoretical zero is a point determined by theory 461° below the zero of Fahrenheit, from which temperature must be estimated in problems connected with expansion of elastic fluids, the volumes being in proportion to the temperatures from absolute zero. This datum will be found essential in considering the question of reheating.

Latent heat is the heat that disappears or becomes latent in change of form, as from a solid to a fluid, or from a fluid to a vapor, and which reappears by condensation when the original condition is resumed.

In the liquefaction of ice 142.5 units of heat per pound become latent, and in the conversion of water into steam 966 units; so that the latent heat of water from ice is 142.5 units, and of steam 966°.

The specific heat of ice is .50, so that the number of thermal units in 1 pound of steam at 212°, measured from absolute zero, will be $(461 + 32) \times .50 + 142.5 + 180 + 966 = 1{,}535$ units.

An apology for these explanations and definitions seems to be required, as they apparently assume a want of information on the part of the reader, but there seems to be a necessity for explanations to remove the ignorance and prejudice that are almost universal. Even in technical journals, articles have appeared from the pens of gentlemen of high scientific reputation advocating the reheating of *dry* air to increase its power, and giving plans of apparatus for the accomplishment of this object. It will be shown that to double the power of dry air by an application of heat is practically impossible, and that it is only by an admixture of vapor that satisfactory results can be secured,yet this demonstration could not be given without furnishing the data which it required.

AIR COMPRESSORS.

The use of compressed air for the operation of rock drills and for other purposes has become so extensive that it has led to great improvements in compressors, and several companies are now engaged in their manufacture who will furnish plants at moderate prices and guarantee results. Among these can be named the South Norwalk Iron Works Company, the Ingersoll Sargeant Drill Company and the Rand Drill Company. The best results are secured by repeated compressions with intermediate cooling, and large plants should always consist of a number of units, so that repairs to one will not affect the remainder, and the number in use at one time can be regulated by the demands of the traffic.

The experience gained by numerous tests, extending over a period of years, has furnished positive and reliable data by which to determine the amount of free air, under compression, required for any given service under any ordinary conditions. If responsible manufacturers of compressors will agree to furnish the plant at a given price, with a guarantee to compress a given number of cubic feet of free air per minute, delivered in station reservoirs under a given pressure, with a coal consumption and horse-power within

prescribed limits, all elements of uncertainty as to cost of power seem to be removed; and this is being done.

The improvements in compressors have greatly increased their efficiency and extended the use of compressed air. In the primitive types an efficiency of 50 per cent. only could be secured; now 80 per cent. is claimed, while the ability to transmit power by this agency to long distances without serious loss, and to concentrate many small powers into a general reservoir will permit many water-powers to be utilized that would otherwise be worthless, and secure economies not offered by any other system.

The sudden compression of air is attended with a great evolution of heat. To compress two volumes of air into one, as previously stated, will raise the temperature 116°; but it is a remarkable and valuable property of air and other elastic fluid, that under high pressures a given increase requires less power and develops less heat than under low pressures.

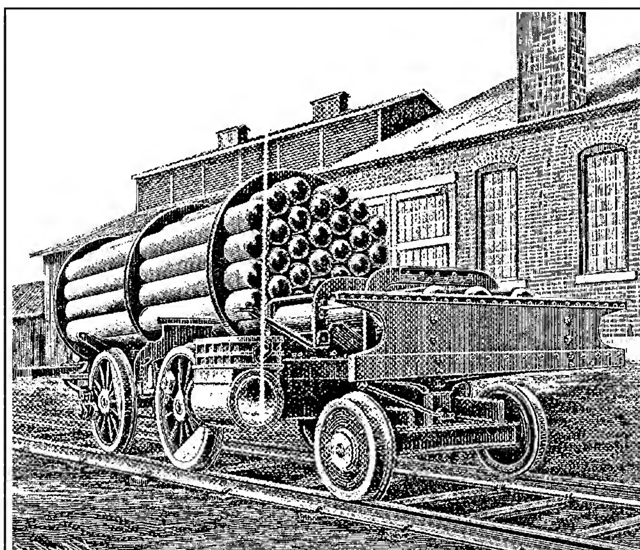
If, for example, it should be required to compress 3,600 cubic feet of free air per minute to a pressure of 500 pounds, the horse-power required would be 1,060 horse-power; if to 1,000 pounds the power would be 1,219 horse.power—a difference of 159 horse-power for 500 pounds; if to 1,500 pounds pressure, 1,288 horse-power, or a difference of 69 horse-power for 500 pounds; and if to 2,000 pounds, 1,339 horse-power, or a difference of only 51 horse-power to gain 500 pounds of additional pressure.

The power required to compress 1 cubic foot of free air is estimated as follows:

	Horse-power.
To 500 pounds pressure per minute	0.316
To 1,000	0.364
To 1,500	0.385
To 2,000	0.400

To which 10 per cent. allowance should be made in practice in allowing actual power for compressors.

Mr. E. Hill, the General Manager of the Norwalk Iron Works, gives absolute isothermal compression to 2,000 pounds per square inch per cubic foot of free air per minute, 0.315 horse-power, and the best possible in practice under the most favorable conditions, 0.378 horse-power. The computation of the writer gave 0.348 horse-power as the theoretical isothermal, but 0.45 should be allowed in practice. It is better to provide an excess of power than to suffer the inconvenience of a deficiency.



View of motor in course of construction, showing battery of compressed air storage flasks.
(Scientific American, January 30, 1897)

RE-HEATING.

A remarkable property of compressed air is that its efficiency can be doubled by re-heating. This is not theory; the fact has been confirmed by actual demonstration, both in Europe and America. It may appear incredible and contrary to well-known physical laws that the efficiency of air can be doubled by simply passing it through a tank of hot water before admission to the motor cylinders, but such is the fact, and the reheating which doubles the power represents a consumption of coal only one-eighth of the amount required at the power station to produce the compression.

A direct test was made at Rome, on motor No. 100, in the presence of Capt. G. J. Fiebeger, of the U. S. Engineers, now Professor of Civil Engineering at West Point. The consumption of re-heated air from an average of many runs was 308 cubic feet per mile. When the re-heater was emptied of water, the volume of cold air required was 669 cubic feet per mile.

An explanation of this remarkable result will be given.

A comparison will be made between the results of reheating dry air to an extent sufficient to double its volume with and without the assistance of water, assuming the volume at 60° to be 300 cubic feet of free air, and that it is to be admitted to the motor cylinders under a pressure of 150 pounds to the square inch.

Assume, in the first place, that air at 60° is passed through a tank of water at 360°, giving a steam and air pressure of 150 pounds per square inch. The units of heat required to double the volume will now be determined.

The absolute temperature at 60° is 60 + 461 = 521°.

The absolute temperature at 360° is 360 + 461 = 821°, so that the air passing through water at 360° will be increased in volume, or under constant volume will be increased in pressure 63 per cent.

The thermal units required for the increase of temperature will be, 23 pounds of air raised 300°, specific heat of air being .24. Then 23 × 300 × .24 = 1,656 units. The air has been increased in pressure 63 per cent., and to double the pressure by the addition of vapor or steam from the water will require the addition of 111 cubic feet of steam at atmospheric tension. That is, the 300 cubic feet of air at atmospheric tension has been increased to 489, and 489 + 111 = 600. The 111 cubic feet of steam weighs 4.3 pounds, to secure which from water at 360° requires only the latent heat, or 863 units. 863 × 4.3 = 3,711, and adding the 1,656 units previously obtained, will give a total of 5,367 units.

Coal completely consumed will furnish 13,000 units per pound, petroleum 20,000 units per pound, and allowing for loss by imperfect combustion, 1 pound of coal or ½ pound of petroleum should furnish the fuel for re-heating at a cost of 2 mills for coal or 1¼ mills for crude petroleum, and 300 cubic feet of air thus re-heated should run an 8-ton motor much more than 1 mile.

To double the volume of air by the application of dry heat, the temperature must be double from absolute zero. At 60° observed temperature the absolute temperature would be 60 + 461 = 521°, and the double would be 1,042°, and deducting 461° would leave the equivalent thermometric temperature 581°, a degree of heat that would burn out the lubricants and would be entirely inadmissible. In fact, it is stated in a recent work on compressed air by Mr. Frank Richards, that to double the power with dry air would

Degrees F.	Cubic Feet.
At 321	35.2
At 300	42.5
At 296	43.3
At 274	48.5
At 259	95.2
At 210	159.0
At 190	238.0
At 182	229.0
At 170	221.0
At 164	459.0
At 158	493.0

require a temperature of about 800°, in consequence of the low specific heat of air and consequent rapid cooling.

As the air is supposed to be used expansively, so that the atmospheric tension is reached at the end of the piston stroke, the quantity of heat lost by expansion with an initial pressure of 10 atmospheres, or 150 pounds, would be 494°, which is nearly all that the heated air contained, so that if the admission could be at 581°, the exhaust would be 87°, without allowance for loss by radiation or conduction, and so much heat would be absorbed by the cylinder that the efficiency of the re-heated air would be greatly impaired.

On the other hand, if the air be passed through hot water, any vapor condensed in the cylinder yields its latent heat and steam, also acts as a lubricant.

Another striking comparison will be presented. Steam at 350° temperature and 150 pounds pressure, will, in cooling down to 212°, impart more than thirty times as much heat to the cylinders as an equal weight of air between the same temperatures.

The difference of temperature is 350 - 212 = 138°. Specific heat of steam, .475; air, .24.

	Units.
1 pound of steam yields 138 ×.475	65.5
and of latent heat	966.0
Total heat from 1 pound of steam	1,031.5
1 pound of air reduced 138° yields 138 × .24	33.12

One pound of steam carries as much heat as 31 pounds of air, and not only serves with little loss to maintain the cylinder and passages at a proper temperature, but, as previously stated, it also serves as a lubricant.

The reasonable conclusion is that it is practically impossible to heat dry air to an extent sufficient to double its power, and if practicable it would be inexpedient and the effect highly injurious.

The ideal re-heater would be a tank containing water at a temperature to furnish steam at the pressure of the air as used in the motor cylinders. The heat retained constant and uniform by cheap fuel, such as crude petroleum, and in winter the cars to be heated by water circulation from the same tank.

From tests made by him in 1879, the writer concluded that the average amount of water absorbed by the air and carried over in the form of steam was about 1 pound for 50 cubic feet of air. The accuracy of this result having been questioned, Mr. Hardie was requested to make a series of tests at Rome, the result of which established the fact that the quantity of water absorbed and carried over was dependent upon the temperature. At a

high temperature in the water a comparatively small volume of air would suffice to evaporate a pound, and at a low temperature the volume of air was greatly increased.

The table [above] is interesting, showing the number of cubic feet of air at atmospheric tension required to absorb and carry over 1 pound of water in the form of steam or vapor.

RESERVOIRS.

The subject of reservoirs is one of the most important in connection with the construction of compressed air motors. The reservoir is the source of power in the motor, and upon its capacity and strength the possible length of run depends. Formerly, reservoirs were constructed of riveted boiler plates, and were capable of sustaining a pressure of from 300 to 600 pounds per square inch only. Consequently, a run of over 10 miles required so great an extension of capacity that room could be secured only by raising the floor to an inconvenient height above the rails. To secure long runs, with moderate reservoir capacity, high pressure is a necessity, and reservoirs are now manufactured, by a peculiar process, from solid ingots of mild steel, without a joint or weld, and which are capable of sustaining with safety a pressure of 2,000 pounds per square inch, the test, within the limits of elasticity, being carried to 4,000 pounds, leaving so large a factor of safety as to render rupture impossible.

It is proper to observe that the risk of rupture is not greater under a pressure of 2,000 pounds than it would be under 500 pounds, for the thickness of the shell would be four times as great with the higher pressure, and the strain per square inch of metal would be precisely the same in both cases.

Paradoxical as it may seem, it can be shown that a pressure of 2,000 pounds per square inch is actually more safe than a pressure of 500 pounds, notwithstanding the fact that newspaper scribblers, in the interest, apparently, of rival systems, to create a prejudice against compressed air, magnify the risks of an explosion and the dangers to result therefrom.

Bear in mind that all reservoirs intended to carry 2,000 pounds are tested to 4,000 pounds, within elastic limits; consequently, the pressure could be increased 2,000 pounds more before the danger limit could be reached.

But if the pressure were 500 pounds the margin of safety would be the same, and the test would be to 1,000 pounds. Consequently, a variation of 500 pounds increase of pressure would reach the danger limit with the low-pressure reservoir, but would be 1,500 pounds below this limit with the high pressure. There can be no question of the sufficiency of the margin of safety.

But if, notwithstanding the theorizing upon the subject, the reservoirs should actually burst, would not the consequences be disastrous ? The answer is no! A rent would be formed and the air would escape with a hissing noise. The material, unlike cast iron, is ductile and will stretch and pull apart and not fly in pieces.

The following extract from a letter from the manufacturers in Germany, addressed to the writer, will afford an explanation:

"Regarding the reservoirs, we put them to a test yesterday to state the elastic limit. It was reached at 3,500 pounds, but we went further in our experiments in order to demonstrate by practical test (as it has been demonstrated in hundreds of bursting tests of

carbonic acid bottles) that these air bottles would not crack or fly to pieces, but that they would simply open when the breaking strain was reached (as was always the case with the carbonic acid bottles, when tested to bursting strain) and allow the contents to flow out, proving thereby that the handling of these bottles is in no way dangerous. We, therefore, think it advisable and safer for the future practical use of the bottles, not to test them, as we mutually agreed, till near to the bursting strain, but only till near to the elastic limits, because we are afraid that although they stand the test till near the bursting strain, the metal is somewhat weakened and, therefore, the practical use afterwards diminished. You will find the bottles somewhat lighter than ordered, and the question to decide for future deliveries will be whether you want the bottles as light as possible and use a storage pressure of 1,500 pounds per square inch, or if you prefer to make them somewhat heavier and use a storage pressure of 2,000 pounds per square inch. Please answer if you agree to the above, and we will send you the whole lot immediately. To-day we send you eight bottles, seven medium long and one short one, that you may, if you choose to do so, repeat the test to 3,500 pounds. As the fluctuations of the compressed air pressure, caused by the fluctuations in the atmospheric temperature are small when compared with the same fluctuations of the carbonic acid, we think it safe to test the air bottles only to the elastic limit,and use them with about half that pressure in practical work, as this way is safer than to test the bottles to the bursting strain and charge them only with one-third of that pressure afterwards in practical use."

Similar results have been indicated by tests in other localities, and it must be remembered that the rupture of a cylinder containing air produces effects that are widely different from those which result from the explosion of a steam boiler. When a boiler explodes, the volume of steam may be instantly increased more than a thousandfold by the conversion of water into steam by the reduction of pressure, the boiler is ruptured and pieces of iron and scalding water projected to great distances, while the rupture of an air cylinder allows a comparative moderate expansion of the contents, accompanied by a sensation of cold and not of heat.*

WEIGHT OF RESERVOIRS.

The weight of reservoirs is in proportion to the number of cubic feet of free air that they inclose, and that again is in proportion to the length of run, and is entirely independent both of diameter and pressure.

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* To illustrate more clearly the effect of the explosion of a steam boiler, let it be assumed that the dimensions of the boiler are 3 feet diameter and 12 feet long, containing 85 cubic feet, of which 70 cubic feet are water and 15 cubic feet of steam at a temperature of 350°.

The 70 cubic feet of water will weigh 4,375 pounds, and at 350° will contain 1,531,250 units of heat.

The 15 cubic feet of steam at 15 atmospheres will weigh 9 pounds and contain 10,602 units, and the whole contents of the boiler 1,541,870 units of heat.

Let x = quantity of water at 212° not converted into steam by the explosion. Then 4,375 - x = water converted into steam at 212° Latent heat, 966 units. Then 212 + (4,375 - x) 966 + 10,602 = 1,541,870. From which x= 3,600 pounds, and 4,375 - 3,600 = 775 pounds of water converted into steam by the explosion = 20,176 cubic feet, 20,176 + 225 = 20,401 cubic feet of steam liberated, and 20,401 + 15 = 1,360 times the original volume of steam which has been increased by the explosion.

The truth of this position can be demonstrated rigidly, but a simple explanation will suffice to make it clear.

Suppose a reservoir of any diameter, say 1 foot, is under a pressure of 2,000 pounds per square inch, 1 foot in length of such reservoir will weigh a certain number of pounds.

Now, suppose the diameter should be reduced to one-half or 6 inches, the thickness of metal to resist the pressure would be one-half as great as formerly, and the circumference also one-half, consequently the weight per foot would be one-fourth; but to secure equal capacity the cylinder must be four times as long, and, therefore, the weight, with a given capacity, must be the same whatever the diameter.

Again, suppose the pressure should be reduced from 2,000 to 1,000 pounds per square inch, the weight to resist this pressure would be reduced one-half, but to contain the same quantity of free air the capacity must be doubled, and, consequently, the weight would be the same as before.

It follows, therefore, that whatever may be the diameter of the reservoir or the pressure per square inch, the weight of reservoir to enclose a given *weight* of air will be constant.

What then is the weight per cubic foot of interior capacity required to resist a pressure of 2,000 pounds per square inch, equivalent to 136 cubic feet of free air?

If 35,000 pounds be assumed as the elastic limit of the material, and one-half, or 17,500 pounds, as the maximum strain upon the metal per square inch from an interior pressure of 2,000 pounds, then it will be found that the weight per cubic foot of interior capacity will be 115 pounds. The weight of the last importation of the German reservoirs was 106 pounds per cubic foot of interior capacity.

As the 115 pounds per cubic foot under 2,000 pounds pressure contain 136 cubic feet of free air compressed into 1 foot, the required weight of reservoir will be 0.856 pound for each cubic foot of free air that may be enclosed.

If, in addition, it should be assumed that 400 cubic feet of free air should be provided to run an 8-ton motor 1 mile, with sufficient allowance for contingencies, the weight of reservoir per mile run would be 338 pounds. This weight, it must be understood, applies to the motor only, and is the equivalent of 42 pounds per ton of motor weight. Trail cars will require only about one-third as much per ton.

RESULTS OF TESTS.

Compressed air motors have long since passed the experimental stage. They have been running for two years at Rome, N. Y., and through the kindness of the officials of the New York Central Railroad have been repeatedly allowed to run on the main track, where a speed has been attained of 30 miles per hour with wheels of only 26 inches diameter.

It should be obvious to every person of intelligence that a compressed air motor can be planned to fulfill any conditions, or perform any service, within the capacity of a steam locomotive. Speed requires large wheels, length of run large storage. High grades and heavy trains require large cylinders. The motor must be adapted to its work and fulfill the conditions of its service.

Tests have been made repeatedly by engineers and experts from all parts of the country, all of whom, without exception, have made favorable reports. One of these tests,

made in the presence of the writer and of Captain Fiebeger, of the U. S. Engineers, February 18, 1895, gave the following results:

Starting with a pressure of 1,900 pounds in motor, and temperature of 291° in the water of the reheating tank, the first six runs of 4,800 feet were made on an average of 221½ cubic feet of free air per mile.

The next six runs of 4,800 feet, temperature 252°, required an average of 339 cubic feet per mile.

The water in the tank was then reheated, by attaching a steam hose, to 302°, when the next run was made on an average of 208½ cubic feet per mile, from which the required quantity of air increased as the water became colder to 377 cubic feet per mile. After the tenth run, the water was again reheated, and the quantity of air fell per mile to 247 cubic feet, and then increased to the fifteenth and last run, when the temperature was 247° and the quantity of air per mile 521 cubic feet.

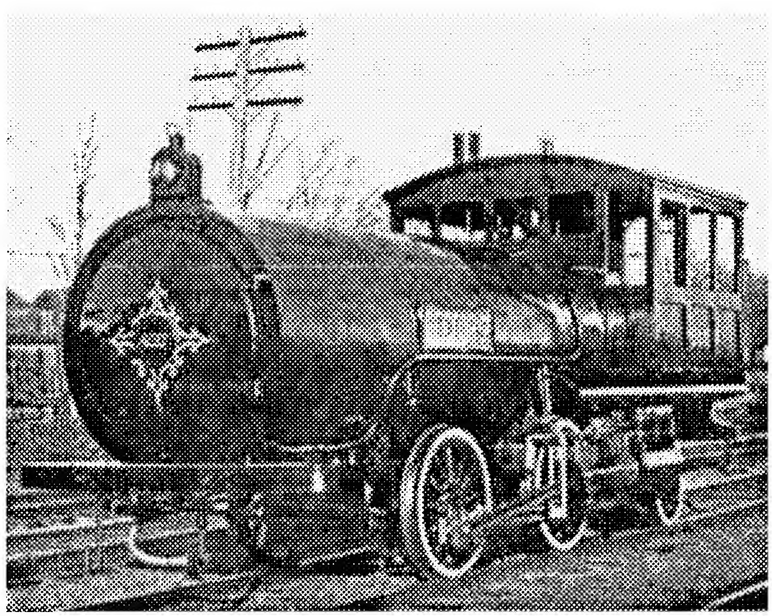
The average expenditure of air during the whole test was 308 cubic feet per mile. When the water was emptied from the tank and cold air used, the consumption was 661 cubic feet per mile on the same track.

This motor was calculated to run a maximum distance of 12 miles, with one charge of air, but as the reservoir capacity was 35 cubic feet, under 136 atmospheres, the cubic contents of free air was 5,760 cubic feet, which, divided by 308, gives 18.7 miles as the possible run if all the air could have been used. Allowing 2.7 miles as a reserve, there would still have remained an effective run of 16 miles. There can be but little doubt that by an efficient system of reheating, whereby the temperature could be maintained at 300°, a greater efficiency could be secured.

It is unnecessary to give the results of other tests; they have been quite numerous, and by different experts, and confirm substantially the conclusion above stated.

The motors now running daily on the One-hundred-and-twenty-fifth Street railway in New York make 17 miles with one charge of air. The reservoir capacity, 50 cubic feet.

Why is compressed air cheaper, both in installation and in operation, than any other system of traction for city and suburban service ?



Hardie compressed air locomotive for the Manhattan Elevated Railway. (Engineering News, June 24, 1897)

It requires less power at the power station for a given service, and this means less cost for engine plant and a perpetual saving in coal consumption.

A comparison with the trolley must be based on similar conditions, and as the recognized maximum distance of

transmission of electrical power under 500 volts is 5 miles, a line of 5 miles, double track, with two-minute headway, will be assumed as a basis of comparison, average speed 10 miles per hour, and 30 motors on line.

Electrical motors are usually supplied with two 25 horsepower motors, making 50 horse-power each, but as the full power is required only in overcoming the maximum resistances, the power provided at the power station is usually calculated upon a basis of transmission of 25 horse-power for each motor.

This transmission involves many losses, and only a comparatively small portion can be actually utilized at the rail.

	Per Cent.		*Per Cent.*
Engine friction	8	Remains	92.0
Belting and shaft	10	"	82.5
Dynamos	8	"	76.2
Transformers at power station	7	"	70.9
Line to sub-station	12	"	62.4
Transformers at sub-station	7	"	51.8
Rotary converter	16	"	48.8
Railway circuit	10	"	43.8
Car motor	15	"	37.2

In the Engineering News of October 17, 1895, p. 256, is found an estimate [see above table], the indicated power of the engine at the power-house being taken at 100.

This estimate gives only 37.2 per cent. of the indicated power at the station as effective at the rail but as other estimates claim a higher efficiency, it will be assumed as 50 per cent.

The thirty motors on the track will therefore require 1,500 horse-power as the prime mover at power-house.

Thirty air motors, with a run of 10 miles, will require 4,000 cubic feet of free air, or 2,000 cubic feet per minute, compressed to 2,000 pounds, and the horse-power at the station will be 900, or 600 less than with electricity, and there is no loss in transmission.

COMPARATIVE COST OF MOTORS.

It is usually claimed that the cost of compressed air motors is considerably greater than the cost of electrical motors for equal service.

This is a mistake; the comparison must be made under like conditions. The compressed air motor carries its power with it. The electric motor takes it from the line. A fair and just comparison requires that the cost of plant to furnish power on the line should be included or omitted in both cases.

Omitting the reservoirs, estimates for the air motors have been brought below the electric motors, notwithstanding the low price of the latter, due to active competition; but allowing the cost to be the same in both systems, a comparison will be made between the reservoirs for thirty motors and the line construction required to furnish the electrical power for an equal number.

The thirty air motors will require 110,000 pounds of reservoir, costing about $15,000; per motor, $500.

The cost of line work for 5 miles of double track, with thirty motors, will be $26,000; per motor, $866.

POWER PLANT.

Another great saving is effected in the cost of power plant. It is usual in electrical estimates to allow $80 per horse-power at the power station, exclusive of land and buildings for engines, boilers, shafting, belts, dynamos and other apparatus.

The cost of 1,500 horse-power, at $80 per horse-power, would be $120,000.

Compressed air requires no dynamos, belting or shafting. Steam from simple boilers is piped directly to the compressor, and it would be an excessive estimate to assume that the cost is one-half that of electricity, or $60,000.

SAVING IN TRACK.

The track for air motors requires no girder rails or electric binding or welding. A simple cross-tie track, as is used for ordinary locomotives, is sufficient. The reason for this is that the weight on the air motor is spring-supported, and on the electric motor a much heavier load is rigidly attached to the axle. From a table furnished to the writer by Franklin L. Pope, it appears that the effect of a blow of 1 ton from a wheel passing over an obstruction 1/8 inch in height, at a speed of 20 miles per hour, is twenty-seven times as great when the weight is rigidly attached as when it is relieved by springs.

The saving with compressed air increases with the magnitude of the plant. Without encumbering this paper with detailed estimates, it is proper to state that the writer prepared a close estimate of the relative cost of electricity and compressed air for a transmission of 5 miles from the power station on an elevated railroad, such as the Third Avenue Railroad, in New York, with trains running at one minute intervals. The estimate for electricity was submitted to a prominent electrical engineer and pronounced correct. The cost was more than double that of the compressed air installation. In fact, the return electrical current could not be transmitted in the ordinary way by rail, but would require some special arrangement. The attempt to reduce the cost of copper by increasing the voltage of transmission is attended with great increase of risk to life.

A system that may prove satisfactory on a small scale and with a limited volume of business may result in failure if extended beyond certain limits. President Vreeland, of the Metropolitan system, in New York, in an interview recently published in the Herald, pronounced the underground electric system in Lenox Avenue unsuited for a line with a heavy business. It required sometimes from two to four days to locate a defect, which, when found, could be remedied in ten minutes. In selecting any system for adoption, the sensible course is always to get estimates in detail from competent and unbiased engineers, covering every point of installation and of operation, and then find responsible contractors to guarantee the work within the limits of the estimates.

COST OF OPERATION.

It has been shown that the cost of installation of a compressed air system is much less than that of the ordinary cheap trolley with wooden poles. If it can be shown also that the operation is more economical, then there can be no question as to its superiority in this

particular over the cable, underground electric and other systems, all of which are much more expensive than the trolley.

The following [table] is the latest revised estimate of an engineer long connected with electric companies and familiar with all details of operation, but at present engaged in the introduction of compressed air installations.

MOTIVE POWER PER CAR MILE
(run 120 miles per day).

	Cents.
Anthracite coal for compressor plant	0.870
Anthracite coal for reheating	0.110
Water, boiler-feed, etc.	0.022
Oil, waste, etc.	0.024
Removal of ashes, etc.	0.014
Operating labor	0.615
Maintenance of power plant, etc.	0.163
Maintenance of motors, etc.	0.280
Interest and general expenses	1.760
	3.858
TRANSPORTATION.	
Maintenance of cars, trucks, buildings	1.619
Motormen, conductors, etc.	6.133
General expenses, interest, etc.	1.155
	12.765
Electricity, similar items included, costs	16.268
Difference, 27 per cent	3 503

SOME INTERESTING FACTS.

By reheating the air required for the operation of a motor, the efficiency may be so much increased that more power may be utilized in the motor cylinders than was expended at the power station in the compression of the air.

This statement has often elicited a smile of incredulity as it seems to be in violation of the law of the conservation of energy, but it is susceptible of a simple explanation.

Take the horse-power at the compressor, say 1,400 horsepower to compress 3,600 cubic feet of free air per minute to 2,000 pounds, the foot-pounds in 10 hours would amount to 5,544,000,000.

The number of motors that this amount of air would supply is 120, assuming cylinders 6 × 14 inches; wheels, 26 inches in diameter; speed, 6 miles per hour; consumption of free air, 300 cubic feet per mile; pressure, 140 pounds per square inch, cut off at one-tenth stroke; mean pressure, 46.2 pounds per square inch. These conditions would give 6,802,272,000 foot-pounds of work in the cylinder of the motors, or 22 per cent. more than the foot-pounds of power expended at the compressor.

How can this be explained? Simply by the reheating of the air, which increases its volume and by the steam which accompanies it and adds greatly to the effect.

But if air is reheated and steam used as an auxiliary to increase the effect, will not the expense of reheating fully offset any advantages thereby secured ?

COST OF REHEATING.

From tests made in 1879, it was found that for 50 cubic feet of free air passed through the reheater, 1 pound of water, in the form of steam, was absorbed; 300 cubic feet of air would, therefore, absorb 6 pounds of water. Under a pressure of 140 pounds, the temperature would be 353°, or for effective pressure of 140 pounds, the absolute pressure would be 160 pounds and temperature 364°. The latent heat at this temperature is 858°.

The heat units required to raise 6 pounds water from 60° to 364°, including the latent heat, will be $1,162 \times 6 = 6,972$ units. To raise the temperature of 300 cubic feet of air 23 pounds, from 60° to 364°, specific heat of air being 0.24, will be $304 \times 23 \times 0.24 = 1,678$ units.

The total units required for reheating for 1 mile will, therefore, be $6,972 + 1,678 = 8,650$ units, which would be supplied by four-fifths of 1 pound of coal, at a cost of 1-1/5 mills.

This coincides very nearly with Mr. Hardie's experience, that the cost of reheating was about one-eighth the cost of compression.

EXPANSION IN REHEATING.

Fifty cubic feet of dry air carries over 1 pound water, which in steam, at atmospheric tension, gives 52 per cent.

Air at 60° F., heated to 364°, will expand in proportion of $461 + 60$ to $461 + 364$, or 521 to 825, which is 58 per cent. Total increase of volume, 110 per cent. Hence, 300 cubic feet will become 633 cubic feet. Without reheating the water on the trip, the Hardie motor, at Rome, consumed 331 cubic feet per mile, 110 per cent. of which would be 695 cubic feet. The actual consumption of dry air was 661 cubic feet.

INFLUENCE OF SPEED IN CONSUMPTION OF AIR.

A very general, but very erroneous, impression appears to exist in regard to the increased consumption of air in traction motors, due to an increase of speed.

It is assumed that the consumption of air must be in proportion to the horse-power, and as the space passed over in a given time must be doubled, the horse-power, in which space is a factor, must be doubled, and the consumption of air doubled also.

This is true, but the consumption of air per mile is not doubled by doubling the speed. The consumption of air is in proportion to the resistances to be overcome, and within reasonable and ordinary limits these resistances are but slightly increased by increase of speed. It is an error, also, to suppose, as many do, that in trolley motors an electrical attraction between the wheel and rail increases adhesion.

In support of these positions, authorities will be quoted. Oscar T. Crosby, in Transactions of American Institute of Electrical Engineers for August and 1894, states: "The adhesive coefficiency between the wheel and the rail is not increased in any practical degree by the passage of the current. In other words, there is no electrical attraction, as some suppose, between the wheel and the rail to increase adhesion. The adhesion is due to the weight on drivers alone."

The train resistances at high speeds do not increase, as is usually supposed, as the square of the velocity. At 86 miles per hour the total resistance per ton was only 13.4 pounds; 347 tons were carried at 86 miles per hour on a line by an expenditure of 1,068 horse-power.

The resistance of the air is a function of the first instead of the second power of the velocity.

From 40 to 80 miles per hour, the tonnage coefficient is practically 8 pounds per ton on first-class roads and best rolling stock.

Wellington, in his popular work on engineering; pages 922-924, makes statements as follows:

"Journal friction is variable, and is usually taken at 8 pounds per ton.

"The load per square inch on journal bearing has very little influence upon the friction.

"The velocity of the lowest journal friction is from 10 to 15 miles per hour.

"With good lubrication there is very little increase of journal friction up to 55 miles per hour.

"The coefficiency of journal friction is approximately constant at velocities from 15 to 50 miles per hour.

"The power required to overcome inertia and accelerate trains is about three times as much as to maintain velocity.

"The additional power required to get up speed is 45 pounds per ton to give 15 miles per hour in 3,340 feet.

"The air resistance at 10 miles per hour is less than 1/5 pound per square foot.

"The principal resistance, except axle resistance, is due to oscillation and concussion, which, at 10 miles per hour, may be taken at ½ pound per ton."

The above quotations from standard authorities do not sustain the statement of the expert of the General Electric Company, who stated in a criticism upon an estimate of the writer, that "a calculation, which it is not necessary to enter into, will show that to make an approximation to the average speed of 20 miles per hour, 600 horse-power will be found *not* sufficient to do the work. Where the speed of an electric train is reduced to that assumed for the steam train (10 miles per hour) 300 horse-power will be found abundantly sufficient."

The inference would appear to be, that if the speed of an electric train is increased from 10 to 20 miles per hour, the power must be increased from 300 to 600 horse-power. If this be true, it is very bad for electricity, for it is not true in regard to either steam or compressed air. The power required must always be sufficient to overcome resistance, and if, as appears from the authorities quoted, the resistances are but slightly increased by increase of velocity, there cannot be any great increase of power required per mile of distance traversed as measured by consumption of air or steam. There must be some, of course, but in ordinary service it does not figure very largely in the expenses.

As practical tests are more satisfactory than theory, the writer requested Mr. Hardie to make a test of the consumption of air at different speeds, and report the result. The table is the report, under date of April 22, 1896.

The above results are very remarkable. The ordinary pressure gauges are not very sensitive, but it is impossible, from the table, to infer that there was any increased

consumption of air per mile, either with a largely increased speed or a considerable increase of weight. When a train is in motion, the draw-bar pull is but slightly increased by a moderate increase of speed. The great losses of power are in acceleration and retardation in starting and stopping.

It has been stated that the power required on a good track to start a street car is 116 pounds per ton, and to maintain it in motion 13 to 17 pounds. On a bad track, 134 pounds to start and 35 pounds to maintain.

Mr. Hardie has found by tests upon his motor that 130 successive applications of the brake consumed, by gauge pressure, 85 cubic feet of free air, equivalent to 0.65 cubic feet for each application.

Franklin L. Pope is authority for the following statement:

"A 16-foot trolley car,weighing about 14,000 pounds, requires eighteen seconds to get up speed and 10 horse-power to run 10 miles per hour, or 1 horse-power per mile per hour at car axle. Three times this power is required during the eighteen seconds of starting."

Frank S. Sprague, in New York Evening Post, of February 8, 1896, states that on the Third Avenue Elevated Railroad the maximum effort in the propulsion of trains is seven times the mean traction on a level; and that to start a train, accelerate to 20 miles per hour and bring it again to rest, consumes eighty seconds.

David L. Barnes estimates that an elevated train of 130 tons can be accelerated to 30 miles per hour in a distance of 1,250 feet, and brought to rest in half that distance.

FIRST TEST. LOAD, 19,150 POUNDS.

Speed	*Cu. ft./mi.*
3.00 miles per hour, consumption of air	 347
5.70	 334
6.81	 488
7.57	 335
7.80	 568
8.50	 452
9.70	 388
10.10	 560
10.30	 275
11.40	 604
12.30	 421
13.00	 538
13.70	 447
16.70	 450
17.05	 447
22.80	 445

SECOND TEST. LOAD, 24,990 POUNDS.

12.27 miles per hour, consumption of air	 334
15.34	 449

THIRD TEST. LOAD, 26,100 POUNDS.

6.70 miles per hour, consumption of air	 437
8.00	 452
10.34	 470

FOURTH TEST. LOAD, 36,000 POUNDS.

5.25 miles per hour, consumption of air	 632
7.50	 582
8.56	 589
15.34	 334

OTHER USES FOR COMPRESSED AIR.

Compressed air affords the most economical means for the transmission of power to long distances. It has been claimed that electrical power generated from waterfalls could

be transmitted hundreds of miles, but the writer has attempted to show in a monograph that is too voluminous to quote, that in the present condition of the science, power by electricity cannot be economically transmitted in competition with power furnished locally by coal, to a greater distance than about 20 miles. Long electrical transmission requires excessively high voltages, which are almost impossible of permanent and successful insulation, and instantly destructive to life in case of accidental contact. The late lamented Franklin Leonard Pope, in a letter to the writer, used this language: "A voltage of 20,000 may be possible in the future, but it has not yet been successfully accomplished. The difficulties seem to increase roughly as the square of the voltage; 10,000 volts is a wicked acting current, and when you double it, you had better watch out." He also adds: "The same speculative boomers who have put in 300 nonpaying electric railroads throughout the country are now at work fostering a craze on electric power transmission. I am sorry to see it, for it will end in discrediting all legitimate electric work. The mass of people will never learn to discriminate between the practicable and impracticable."

The transmission of compressed air requires high pressures, for the reason that increased pressure gives increased density and reduced volume and velocity. The loss in transmission being as the first power of the density and the square of the velocity, the loss in transmitting under 200 pounds would be ten times as great as under 2,000 pounds. High pressures are necessary for economical transmission both with electricity and air.

But compressed air and electricity are not properly to be considered antagonists; they may be made valuable auxiliaries.

A 6-inch pipe under an initial pressure of 2,000 pounds per square inch, and a terminal pressure of 10 atmospheres, or 147 pounds, will transmit nearly 8,000 horse-power to a distance of 10 miles, 5,700 horse-power to 20 miles, and 2,500 horse-power to a distance of 100 miles. Where there are mountain streams furnishing small powers at frequent intervals, a number can be concentrated in one pipe, and transmitted to furnish large power in distant localities. Compressed air, thus economically transmitted, can be used to generate electricity for local purposes. It can also be distributed to provide small powers, and also for ventilation and refrigeration in towns and cities.

The cable and electric systems, it is well known, are operated to best advantage economically at full capacity, but this is only for a few hours in the day. If surplus power were used to store air at high pressure in reservoirs the machinery could be shut down entirely or partially, and compressed air motors substituted at night and during the hours when full capacity is not required.

ELASTICITY OF THE SYSTEM.

An important advantage of compressed air motors is found in the fact that each motor is independent, and unaffected by any derangement of feed or trolley wires, cables or dynamos. They can run on any line, in connection with any other system, and at any rate of speed. The introduction of air motors can be gradual; one motor can be tried, and, if satisfactory, the number can be increased to a full equipment. The steam required for electric or cable lines can furnish the little that is required for an experimental compressor, and will be more than sufficient for a full equipment. No outside expenditure whatever is required—no conduits, poles or wires. In this respect it differs from other systems, and permits a test to be made at a minimum of cost; but compressed air motors can no longer

be considered as experiments. While they may not have attained the utmost limit of perfection of which they are capable, the experience in Europe, in Rome, N. Y., and in the City of New York, should be sufficient to satisfy the most skeptical.

The Hoadley-Knight Compressed Air Locomotive1896-1900

"Compressed Air Motors," <u>Street Railway Journal</u>, August, 1897.

In a review of the mechanical tramway systems of Europe by E. A. Ziffer, read before the International Street Railway Association at its last annual meeting at Stockholm, the statement was made that compressed air cars were then in use on seven lines in Europe, aggregating about 40 miles of track and that several other lines were in course of construction. The General Omnibus Company of Paris has had compressed air motors on three of its lines for a number of years and they are giving, according to the general manager of the company, excellent satisfaction. Many attempts have been made in this country to operate compressed air cars, but up to recently with exceedingly discouraging results. The value, however of a motive power for street railways that will obviate the well known objections to trolley lines, and the enormous expense and delay of equipment of conduit lines, has brought about within the last year a very rapid development of compressed air, as a motive power for this purpose.

Reference has previously been made to the motors of the Compressed Air Power Company which has installed a number of motors in New York City and has during the last month put some motors in operation on the Eckington & Soldiers' Home Railway in Washington, D. C. This company was formed a little more than a year ago by several prominent New York and Philadelphia capitalists headed by Wm. C. Whitney and Thomas Ryan, of New York, and Messrs. Elkins, Widener and Dolan, of Philadelphia, The engineers secured by this syndicate to develop this system were two young men of long experience in electric and cable railroading, J. H. Hoadley and Walter H. Knight.* The latter has been chief railway engineer of the General Electric Company and one of the pioneers in electric railroading while the former is a prominent designer and builder of electric railways. These gentlemen approached the problem from an entirely novel standpoint, following rather the lines of the electric motor equipment than those of compressed air cars, as the latter had been built theretofore. They sought first a motor that would be like an electric motor—iron clad, and resting with one end upon an axle, to which its crank shaft was geared.

The unsatisfactory results attending the use of side rods and exposed machinery, in connection with the electric motor, were, of course, well known, and it was realized at once that in any form of air motor it was essential that the moving parts should be enclosed in a case where they could run in oil free from dust, and where they would lubricate themselves continuously without the attention of the operator. It also seemed extremely desirable to continue the use of standard street car wheels, axles, trucks and car bodies, as these have all reached a standardized form which is known to insure the least expense of maintenance.

* Hoadley and Knight were at one time involved with Nikola Tesla as partners in a plan to develop his bladeless turbine as a prime mover.—Editor.

Owing also, to the limited intelligence of the motor man, and the necessity of more prompt control than is had with steam locomotives, it was considered necessary to develop a controller, which could be operated by a single handle to perform all the various functions of the controller in their proper sequence without requiring thought on the part of the motormen. These three features of iron clad motors, running in oil, standard street railway rolling stock and single handle controller, were therefore made the distinctive features of the-Hoadley-Knight system, which may be described more in detail as follows:

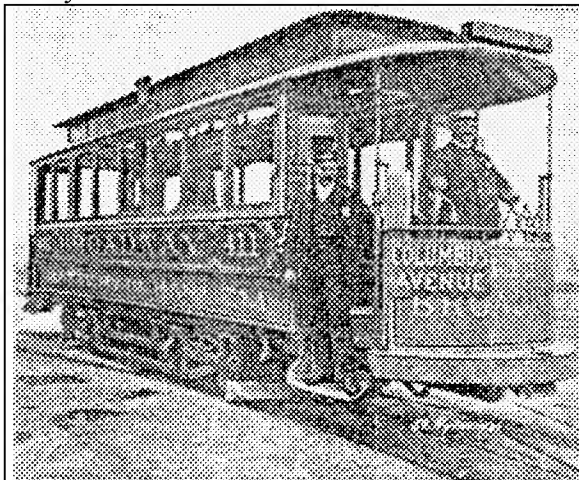


Fig. 1.—Compressed Air Motor Car, New York.

On each axle is mounted an iron clad motor, having two cylinders and cranks at right angles. One motor has two high pressure cylinders, 3½ ins. diameter and 6 ins. stroke, and the other motor has two low pressure cylinders, 7 ins. diameter and 6 ins. stroke. Upon the crank shaft is a a pinion, about 9 ins. in diameter, meshing into a 23 in. gear wheel mounted on the middle of the axle; the axle is straight, as used for electric motors, and the wheels are ordinary street car wheels. The motor consists essentially of a cast iron case or basin, to which the two cylinders are bolted and in which all the moving parts, the piston rods, crossheads, connecting rods, cranks, gears, valve rods, eccentrics and reversing mechanism are located. The basin is covered with a lid which can be quickly removed, thereby exposing all the machinery for complete inspection. A sufficient quantity of oil is introduced into the basin to keep the moving parts continuously drenched with the lubricant, thus insuring for them the longest possible life; and reducing to a corresponding degree the maintenance account.

The air reservoirs, in the shape of seamless steel bottles, are under the seats of the car, and a pipe leads from them to a combined reducing and throttle valve, which reduces the storage pressure to the working pressure. The pipe before reaching the reducing valve passes around the heater, so that the air can receive sufficient heat to prevent freezing any moisture that may be in it.

The heater consists of a seamless flask charged with hot water under a pressure of from 150 lbs. to 250 lbs.

The air on leaving the reducing valve passes through a coil kept hot by the heater to a temperature corresponding to the steam pressure of the hot water, and is then introduced into the high pressure cylinders, both of which are in one motor on the axle. During its passage between the reducing valve and the high pressure cylinder means are provided for injecting a certain amount of moisture into the air, this having been found to give certain advantages as will be described later. In exhausting from the high pressure motor the air is again heated and passes through the low pressure motor on the other axle, from which it escapes through a muffler into the atmosphere. By having one motor high pressure and the other motor low pressure, undue slipping of the wheels is prevented, as when the high pressure wheels slip the low pressure motor gets more air and more

pressure, and the back pressure from the receiver tends to stop the slipping. When the low pressure motor slips its wheels, it draws down the receiver pressure and thereby weakens itself, correspondingly increasing the strength of the non-slipping motor. The direction of the flow of the air is shown in Fig. 3 where *R R* are the air reservoirs, *V* the reducing valve, *H* the heater, *M M* the motors.

Twelve months' operation have demonstrated that these motors are highly efficient and exceedingly durable, all of the original parts being still in use. The manufacturers estimate that making a liberal allowance for the wear and tear that must occur and which, in the case of the more rapidly wearing parts, has been measured, the maintenance per car mile can be figured at not more than one cent, which compares favorably with that of the electric motor. [see table]

The motors are capable of slipping the wheels on a dry rail under a weight of 30,000 Ibs., and are therefore as powerful as the heaviest electric motor equipment. The total weight is little, if any, more than that of an equally powerful electric equipment, and the rigid weight on the axle, to which maintenance of track is mostly charged, is considerably less.

The weight of the standard Hoadley-Knight air car is tabulated as follows .

Car body	6,000	lbs.
Trucks	4,500	
Air reservoirs	3,000	
Heater	500	
Motors (each 1500 Ibs.)	3,000	
Controlling apparatus	400	
Piping	150	
Total	17,500	lbs.

The air consumption of these cars varies from 30 Ibs. to 40 Ibs. per car mile, for a 34 ft. car of the Broadway type. About 111 Ibs. of air can be compressed to 2000 Ibs. per square inch per horse power hour. The cars require therefore, on an average a little over 3 h.p. hours per car mile, which in a modern compressor, running on a steady load and pumping into a reservoir of ample capacity, can be produced, it is claimed, for one-half cent per horse power hour, including all power house charges. To this must be added the cost of the hot water for reheating, which is given by the engineers of the system as one mill per car mile. The motive power expenses per car mile on this basis are therefore estimated as follows: [see table]

COST PER CAR MILE OF MOTIVE POWER.

3½ h.p. hours at ½ cent.	$.0175
Hot water for reheating	.0010
Maintenance of motor equipment	.0100
Total	$.0285

This compares favorably with the best that has been done with electric motors. The storage capacity for a run of 17 miles would be 45 cu. ft.

The Hoadley-Knight motors are controlled by varying the cut-off as well as by the throttle, the two being operated simultaneously. This method of controlling is adopted because it not only gives the highest efficiency, but also gives the greatest range of power. A car can be started with a promptness only limited by the friction of the wheels on the rails, or may be started with almost imperceptile acceleration. In common with other air cars, the start is easy and free from jerks.

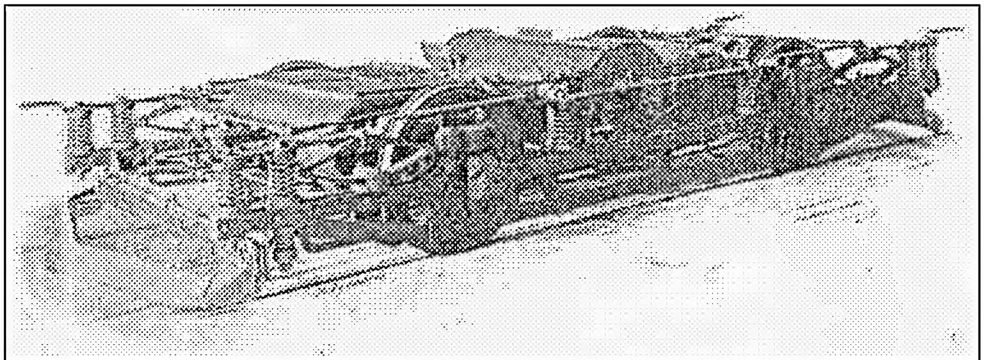


Fig. 2.—Side View, Compressed Air Motor Equipment on StandardBroadway Truck.

A forward movement of the single controller handle starts the car and the propelling force is proportional to the distance that the handle is moved from its starting point, so that any degree of acceleration can be obtained. A backward movement to the starting position brings the valve to a minimum cut-off and closes the throttle. A still further backward movement reverses the motors and opens the throttle to back the car. The inventors claim that anything less simple than this is not feasible, or indeed safe for street car work, and they point out as sustaining this view, that the only successful electric controllers have been substantially as simple. Of course, with an electric motor the reversing handle has been kept separate, as it is undesirable to reverse an electric motor, but with an air motor there is no objection to reversing, and there is therefore no need of more than one handle on this account.

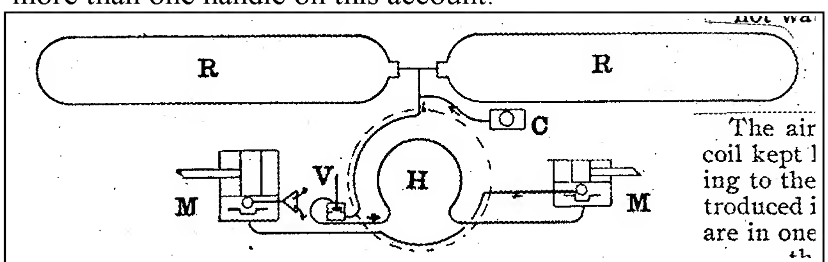


Fig. 3.—Diagram Showing Flow of Air

The inventors have made a large and exhaustive series of experiments on the subject of the heater. They have tried all the known forms. Their first experiment with the Mékarski heater, which is the one generally in use on air cars and in which the air is made to pass up through hot water, proved to them that such a method is liable to bring excessive quantities of water over into the motors, when heavy demands are made upon the air. They also found, what had not been generally recognized until they announced it, that such a heater, when the contained water is under a pressure exceeding that of the air, runs the motor, practically as a steam engine, with too much visible exhaust and too little air, and that after the pressure of the water in the heater falls below that of the air, practically no steam is generated, and the air enters the motor practically dry. Their experiments with dry heaters showed them that the same economy could be obtained with dry heat as with wet, but the heater itself proved objectionable and difficult to regulate. This brought about a return to the hot water heater, but with certain precautions against admitting the air to the water, which proved highly satisfactory.

Their experiments with air reservoirs have been probably the most extensive ever made. They have tried large numbers of each of the five different prominent manufacturers and have experimentally blown up all kinds repeatedly, both with air and water, and find that they are all very much alike, both as regards strength and character of rupture. They are now using the Ehrhardt flasks. It seems to be generally admitted that the air motor would have reached a practical state of perfection much earlier, had it not been for the slow development of the art of making high pressure flasks, which until the last few years were not obtainable of sufficient strength to give the desired capacity within a reasonable space.

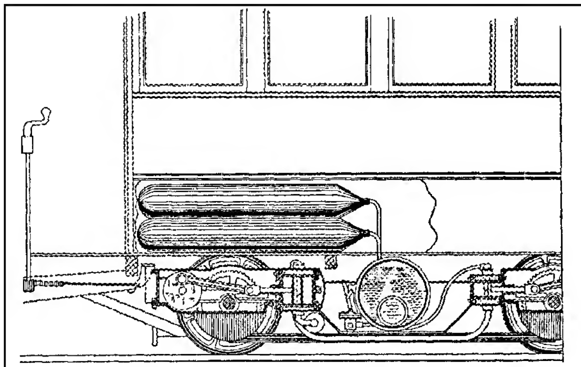


Fig. 4.—Sectional View of Motor Car.

One of these cars will run 15 miles on a good track on a charge that is restricted to a space under the seats, and this could be even increased to 20 miles by crowding in all the flasks that the space could allow.

As the air pressure in the reservoirs is always limited to that which the compressor can give, and as the reservoirs themselves are capable of withstanding nearly three times this pressure, it will be readily seen that the element of danger is practically eliminated. There is no possible way in which the air pressure can be increased to the bursting pressure of the flasks. Furthermore they are protected by a safety pop set to open at a pressure slightly above that given by the compressor. There is no deteriorating influence incidental to their use. There has never been an explosion with any of these flasks by air, except when premeditated, and only then with the greatest difficulty and with apparatus especially constructed at great expense to bring the required force into play. Every flask is tested to 2½ times its working pressure before being used. Steam boilers are only tested 1½ times the working pressure.

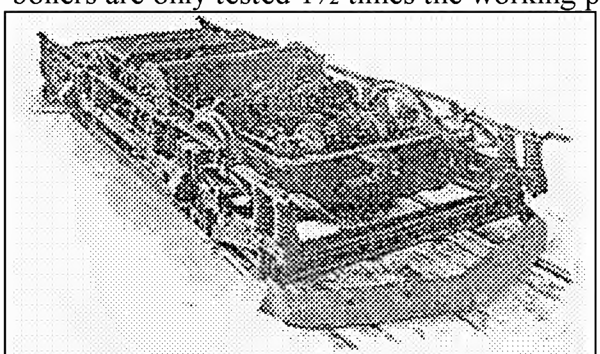


Fig. 5.—Top View, Compressed Air Motor Truck.

The placing of the motor in the middle of the axle and the driving of the axle in the middle, by means of the gear, does away with all lateral oscillation, so common in side rod motors.

The car presents an appearance like that of an electric car without the trolley accessories, and it is claimed to accelerate as quickly, to run as fast, to be as free from vibration, start with greater ease, stop with greater promptness (owing to lack of momentum of armatures) and to possess in general all the advantages of the electric car, without any of its disadvantages.

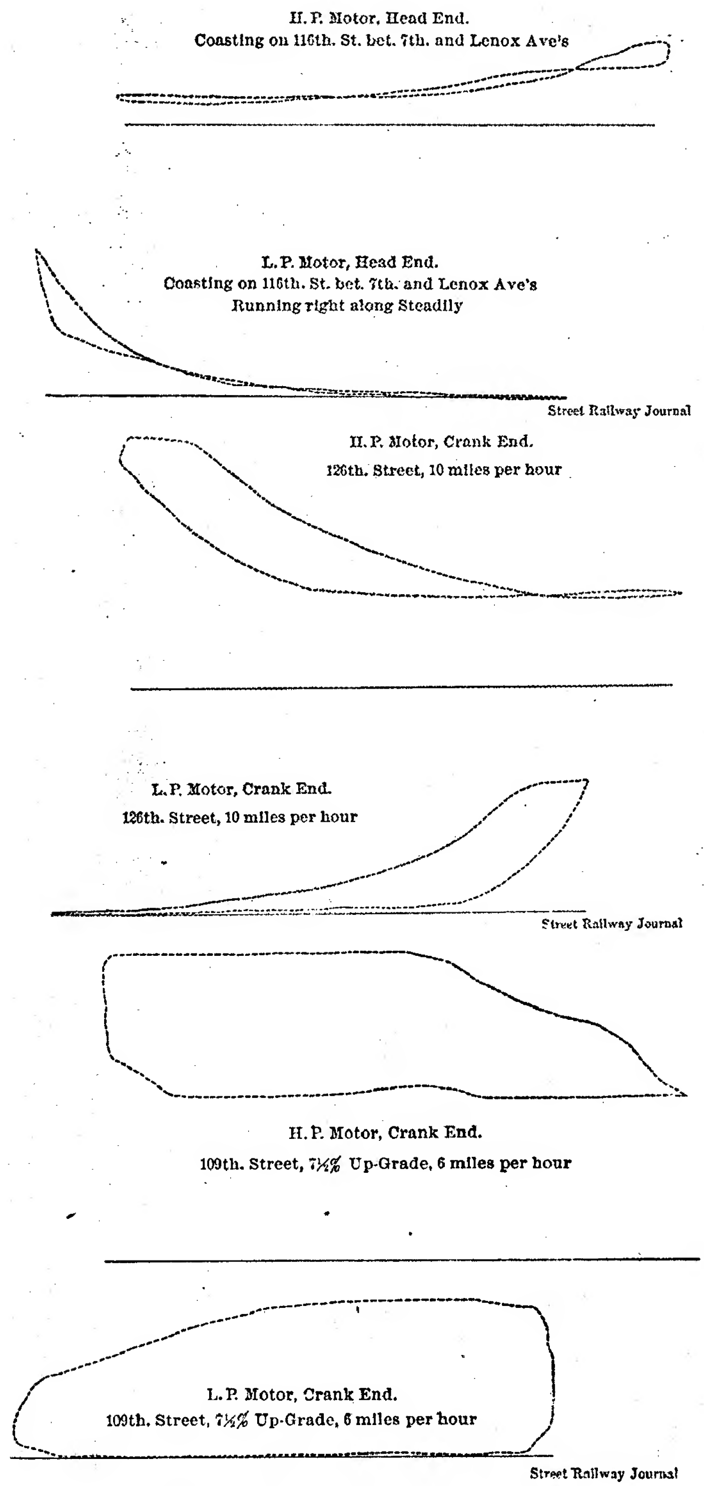
It is true that every two hours the cars must be charged, but this is done in two minutes and at the end of the line, where it does not inconvenience the passengers, and therefore, so far as the traveling public is concerned, is attended with no disadvantages.

To the street railway man it means practically almost no additional expense, as in general a wait of at least two minutes is made at the end of the line.

As compared with the storage battery car, which in its absence from dependence upon a distributing system the air motor resembles, the latter is claimed to possess the following advantages:

1. Its storage cells cost very little, comparatively.
2. They are a permanent investment, requiring practically no repairing.
3. The reservoirs can be charged in two minutes instead of six hours.
4. An exhaustion of the battery does not injure it (as with the sulphating of the electric battery).
5. The weight is about one-half.
6. There is no odor.
7. There is no corrosive liquid to slop over, or injure operatives' hands.
8. In case of necessity it can be charged along the line without leaving the line.

Barring fuel burning motors, which seem to be by common consent ruled out of the sphere of street service, compressed air stands alone as the only available stored force, which suffers no loss or deterioration while stored, which is instantly available, which requires no skill to utilize it and which is absolutely free from any offensive products. It is due to these practical features that compressed air has been so successful as a transmitter of force in mining work and air brakes, and the same advantages, it is believed by its promoters, will bring about its very general adoption for propeling vehicles.



Figs. **6, 7, 8.—Typical H. P. & L. P. Motor Indicator Diagrams.**

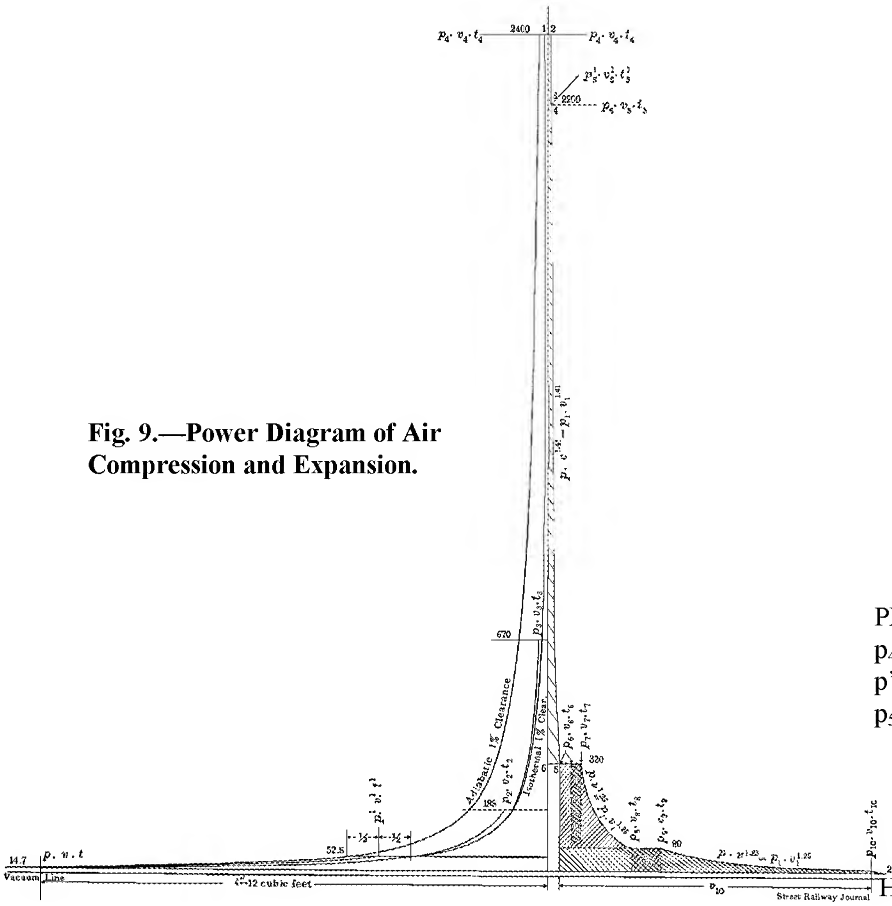


Fig. 9.—Power Diagram of Air Compression and Expansion.

Scale of absolute pressures—360.
Scale of volumes 1" = 3 cu. ft.
Compression vol. = ½ way between adiabatic and isothermal vols.

AIR COMPRESSOR DIAGRAM.

Area 1st stage diagram = .233 sq.in.
Area 2nd stage diagram = .215 sq.in.
Area 3rd stage diagram = .182 sq.in.
Area 4th stage diagram = .100 sq.in.
Total, = .720 sq.in.

PRESSURES, TEMPERATURES AND VOLUMES.

$p_4 = 2400$	$v_4 = 0.04$	$t_4 = 60°$
$p'_5 = 2200$	$v'_5 = 0.0436$	$t'_5 = 60°$
$p_5 = 2200$	$v_5 = 0.0726$	$t_5 = 406°$

High press. heater

$$\left\{\begin{array}{l} p_6 = 320 \\ v_6 = .2854 \\ t_6 = 35° \\ p_7 = 320 \\ v_7 = .4959 \\ t_7 = 400° \end{array}\right.$$

$$\text{Gain in vol.}^6 = \frac{v_7 - v_6}{v_6} = 73.7\%$$

Low press. heater

$$\left\{\begin{array}{l} p_8 = 80 \\ v_8 = 1.7067 \\ t_8 = 98° \\ p_9 = 80 \\ v_9 = 2.3907 \\ t_9 = 300° \end{array}\right.$$

$$\text{Gain in vol.}^5 = \frac{v_9 - v_8}{v_8} = 40\%$$

$p_{10} = 20$
$p_{10} = 7.396$
$p_{10} =$

Area Engine Diagrams.

x { Area high press. diagram = .189 sq. in.
Area low press. diagram = .244 sq. in.
Total, .433 sq. in.

y{ Area 1, 2, 3, 4, 5, 6, 1 = .245 sq. in.
Total area, whole diag. = x + y = .678

$$\text{Efficiency of engine} = \frac{.433}{.678} = 59.3\%$$

When clearance in high p. cylinder = 10%
When clearance in low p. cylinder = 6%

"...Barring fuel burning motors, which seem to be by common consent ruled out of the sphere of street service, compressed air stands alone as the only available stored force, which suffers no loss or deterioration while stored, which is instantly available, which requires no skill to utilize it and which is absolutely free from any offensive products. It is due to these practical features that compressed air has been so successful as a transmitter of force in mining work and air brakes, and the same advantages, it is believed by its promoters, will bring about its very general adoption for propeling vehicles...."

The compressor problem for the high pressures used in this system is one which has required an especial amount of investigation.

It was found that the three stage compressors were unsatisfactory. For one thing, the temperature conditions required at least four stages to prevent the carbonization of the lubricant, and a four stage, belt driven compressor was constructed in demonstration of this and other points and was used afterward to run cars in Washington, D. C. With this compressor, a new system of compressor valves was worked out, with a view of saving the frequent renewals caused by such valves as were previously used. With the new style of valves this compressor has shown a capability of being run continuously night and day at full speed for six months. without requiring any renewals. The valves are of such simple construction as to cost almost nothing for renewal. With a four stage compressor there is not only the improvement due to better treatment of the lubricants, by reason of the lower temperatures, but also less back leakage, and greater economy to the extent of about 10 per cent., or more, as compared with a three stage compressor having the same elements of improved detail. As compared with any three stage compressor the market has heretofore offered, the saving is claimed to be much greater.

Taking advantage of the experience gained from the experimental four stage compressor, E. K. Hill, engineer of the AmericanWheelock Engine Company, designed a line of large compressors of a novel type, from which the builders claim to be able to produce most satisfactory results in extreme high pressure work as regards economy and durability. This type is shown by the accompanying side elevation which will give a general idea of the machine.

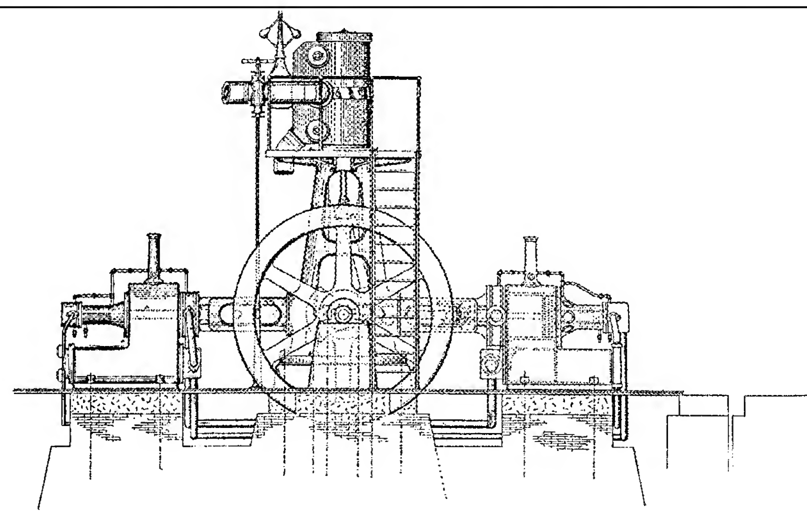


Fig. 10.—Four Stage Air Compressor.

The steam end is a vertical engine of ordinary kind in general, but specially adapted to have connected upon each side of the column, the horizontal air compressing ends each of which has two stages arranged in tandem form. The steam end drives a center crank with shaft resting in bearings on each side. The crank shaft has a triple construction, i.e., there are three crank pins, one being driven from the steam end while the others serve to drive the compressor ends. These pins cannot, of course, be in the same vertical plane, but they are large in diameter and correspondingly short, so that in effect the center lines of the steam and air ends are in the same plane. Furthermore the steam and air cranks are of different lengths, the stroke thus differing, the steam end having a longer stroke. By this construction the proper relation between the piston speeds of steam and air ends is secured.

By this general arrangement of steam and air elements in the machine, the relation of power applied to resistance offered is extremely favorable to a uniform turning effect, so that a relatively small flywheel suffices to give the necessary regulation. The forces exerted oppose and balance to a degree that renders the total friction of the machine very small.

The arrangement and means of driving the air compressing cylinders is clearly shown in the illustration This design gives directness and rigidity in highest degree The air cylinders are mounted within and supported upon beds or housings which constitute water tanks for jacketing the cylinders and intercoolers, the latter consisting of tubes placed in the lower part of the housings. The cylinders are jacketed over the entire barrel and head, and an intercooler is provided between each cylinder as well as one for the final delivery. When consideration is given to all the pipe connections and other details necessary for the air and water in four stages, it will be evident that this design is singularly compact and direct.

The cylinders are all single acting and fitted with special care to secure tightness of pistons. The air valves are made upon a novel system the result of extensive experimenting. All usual forms of valve that were tried were found inadequate to answer the severe requirements of endurance and tightness under heavy pressures. The valves are conveniently accessible without disconnecting any main part of machine, and can be replaced in a few minutes.

The machine as shown has a single steam cylinder, and has the outboard end of shaft carried in a bearing. The design is such, however, that the shaft of a duplicate machine can be connected, thus forming a duplex compressor with a single flywheel between, and using compound steam cylinders, or the single machine can be fitted with vertical, tandem, compound cylinders.

The steam end is supplied with a high grade automatic cut-off valve gear, and all the details have been worked out with great care, the special features having been developed by exhaustive experimental use. It would seem that the claims of the builders that they have a unique and extremely efficient compressor in an entirely new class of machines, is well founded.

The power diagram shown in Fig. 9 illustrates in a graphic manner the effect upon the air during the four stage compression, and the subsequent two stage expansion; the left hand half of the diagram showing compression, and the right hand expansion. The compression side shows how closely the four stage compression approximates the isothermal. The adiabatic curve from atmosphere to 2400 Ibs., also is shown, to give a graphic idea of the saving in power effected by the use of four stages. On the right the curve illustrates the loss, due to charging the car, when the pressure falls from 2400 Ibs. to 2200 Ibs., and the loss due to the reducing valve, when the pressure falls from 2200 Ibs. to 320 Ibs. Below this the high and low pressure cards show, by cross hatching, the gain in power due to reheating, and the ratio of the area of these two cards to the area of the compression cards, gives us what might be called the thermo-dynamic efficiency, which in this case is 59 per cent. The accompanying data will explain the diagram more in detail.

Assuming 100 i.h.p, in the engine during the compression, there is found to be a loss of 20 per cent in the friction of the engine and compressor. Of 80 h.p. thus exerted in compressing the air, 40 per œnt is lost in the subsequent reduction of the pressure. Of the 48 h.p. developed in the motor cylinders, there is a further loss by leakage of about 10 per

cent and the friction of the motor brings the residual power delivered to the axle down to 35. This comparatively low efficiency is largely offset by the fact that the compressor runs on a practically constant load, and at a correspondingly high efficiency.

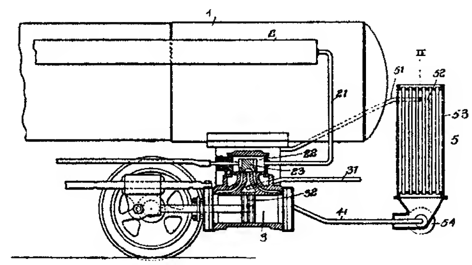
The expense of installing this system does not differ materially from that of the electric trolley system. The compressed air power plant can be installed for the same amount as an electric power plant, and the cars, while costing somewhat more than the trolley cars, are more than offset, it is claimed, by the expense of the trolley line itself. As compared with the underground trolley, there is of course, a saving of the interest and maintenance of the conduit, a sum which would in itself exceed in many cases the whole motive power expense of the compressed air car.

Chapter 12: The Technical Press after 1900

The H. K. Porter Compound Air Locomotives, 1896-1930

U. S. Patent No. 868,560, Interheater for Compound Compressed-Air Engines, Patented October 15, 1907, by Charles B. Hodges of Pittsburgh, Pennsylvania

1. In a compound compressed-air engine in combination with the high-pressure and low-pressure cylinder and their inlets and exhausts, of a receptacle for compressed air connected with the exhaust from the high-pressure cylinder and with the inlet to the low-pressure cylinder, and means for causing a current of air to blow over the surface of the said receptacle operative on the exhaust of air from the low-pressure cylinder, substantially as described...



Patent No. 868,560

(Abstract from the Patent Gazette; patent application filed Oct. 10, 1904. The next section is an article written by the same inventor, after his patent was filed but before it was granted. Note his emphasis on the use of ribbed cylinders to absorb ambient heat. His pending patent was for a more advanced process accomplishing the same end. This is Hodges' first patent on solar pneumatic locomotive engines. For more information, see the chapter on "The Most Efficient Air Engines Ever Built." The H. K. Porter locomotives that Hodges discusses in the article below were the forerunners of the interheated compound locomotives built from his patents. Hodges assigned all his patents to the H. K. Porter Co.)

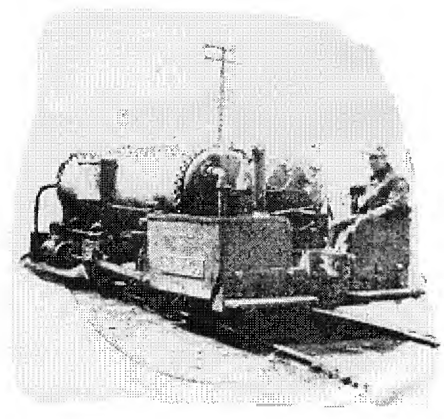
"An Industrial Compressed-Air Railway," Charles B. Hodges, Cassier's Magazine, Vol. 28, 1905.

The machinery on these locomotives is in most respects the same as would be employed on a steam locomotive of the same size, the chief difference being that the cylinders are ribbed, in order that they may the more rapidly absorb heat from the atmosphere, instead of being lagged to prevent the loss of heat, as is the case with steam locomotives at atmospheric temperature, and falls to a temperature far below that of the atmosphere during the expansion in the cylinders. This feature has an important bearing upon the relative efficiencies of the three great powers,—steam, electricity and compressed air, under certain conditions.

An electric motor is an inefficient machine while coming up to normal speed; a steam engine is inefficient until the walls of the cylinders are thoroughly heated; but a compressed air engine is most efficient, thermodynamically, with the first movement of the piston, because the walls of the cylinders are then at their highest temperature. This fact would point to the use of compressed air locomotives wherever stops and starts are to occur with great frequency. The main storage tanks on the air locomotives replace the boiler, and need but little description. They are exceptionally good pieces of work, having

required no repairs during four years of service; they are to-day practically bottle-tight. The locomotives stand for hours without perceptible loss of pressure.

The regulating valves on the locomotives deserve special attention. To make the locomotives successful this piece of apparatus must at all times maintain, with the minimum amount of attention, a practically uniform pressure in the small auxiliary reservoir located between the regulating valve and the throttle valve, and be absolutely tight when the locomotive is at rest. How well the regulating valves on these locomotives perform is evident to anyone who rides on them. The gauge-hand that indicates the pressure in the auxiliary reservoir is apparently glued to the 150-pound mark on the gauge while the locomotive is in motion, and it seldom rises above 175 pounds while the locomotive is at rest.



The compressed air required by the locomotives is furnished by two compressors, having cross compound steam cylinders equipped with Corliss valve-gear, and four-stage air cylinders. The compressors are duplicates. The high-pressure steam cylinder is 20 inches, and the low pressure steam cylinder, 40 inches in diameter; all air cylinders are single-acting; the intake air cylinder is 37¼ in diameter, first intermediate cylinder 20¼ inches. second intermediate cylinder 12½ inches, high-pressure cylinder 6 inches, and the common stroke is 48 inches. The intake and first intermediate cylinders are placed behind one steam cylinder: the second intermediate and high-pressure cylinders behind the other. All the air cylinders are water-jacketed, and intercoolers are provided for cooling the air after each stage of compression.

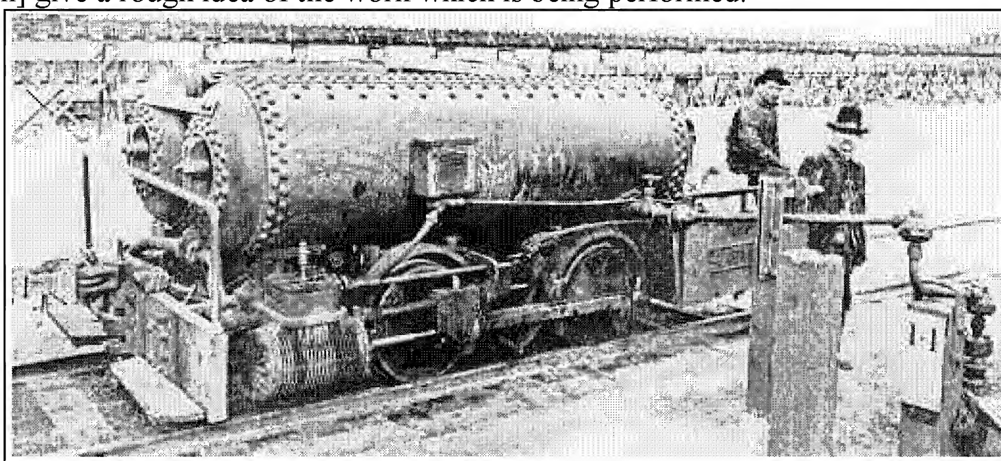
The compressors are equipped with automatic speed and pressure governors, and an examination of the sheets taken from the recording gauge shows that the regulation of pressure is absolutely perfect. They are operated with steam at 150 pounds pressure and with a vacuum of 17 inches in the condenser, perfect vacuum at the elevation being 24 inches. The rated speed is 70 revolutions per minute: the horsepower developed per revolution, 8.7; the steam consumption per horsepower-hour when operating at a speed of 55 revolutions per minute, 18.67 pounds. The company intends to improve the vacuum in the near future, which will undoubtedly result in a lower steam consumption.

The remainder of the haulage equipment consists of a system of piping varying in size from 2 to 6 inches. This serves two purposes:—First, it connects the compressors with the various charging stations; second, it provides a reservoir containing a reserve supply of compressed air at a pressure in excess of that required by the locomotives, and sufficient to charge one or two locomotives instantaneously. Although this pipe line sustains a pressure of 950 pounds per square inch and consists of several thousand feet of pipe of various sizes, with many branches, valves, and charging station connections, leaks are extremely rare and it requires a rather tedious search to discover one. The losses due to this cause must be small indeed, as a leak of any importance is readily heard by any person within a radius of 10 feet.

The compressed air locomotives are operated over about 18 miles of standard gauge track laid with 60-pound rails, located inside of an irregular area about half a mile square. The reduction works are located on a side hill, and the locomotives, in doing their varied work, pass from the bottom of one building to the top of another, under the dripping bins from which the concentrates are drawn, and over, under and around the furnaces, in an atmosphere of heat, dust and sulphurous acid, with sharp curves, steep grades, and loads that tax their capacity to the extreme limit.

Outside the buildings the locomotives are subjected to extremes of weather. At an elevation of 5000 feet above sea level, at Anaconda, Mont., the range of temperature is from 95 degrees above zero to 35 degrees below with heavy snows and high winds. Under these conditions the records of the company show that the compressed air locomotives, during the months of January, February, and March, 1905, lost 5¾ hours for one locomotive out of a total of 22,320 locomotive-hours, distributed among thirteen locomotives. These records show all delays chargeable to failures of the transportation system and are kept with great exactness.

The new reduction works were first operated in February, 1902. The locomotives in question have been the only means of internal transportation since the first pound of copper was produced. and the nine original locomotives, purchased in November, 1900, which were used during construction, are still in service and apparently as good as new, except for the necessity for regular running repairs. The tabulated data on this page [not shown] give a rough idea of the work which is being performed.



A locomotive being charged with air. The entire operation of coupling, charging, and uncoupling is frequently performed in less than a minute and a half. All the compressed air locomotives consedered in this article were built by the H. K. Porter Co., Pittsburgh, PA.

It should be understood in reviewing the table that it does not by any means represent all the work done by the locomotives. The first omission is the movement of the locomotives themselves, both when hauling trains and when running light from point to point; second, the endless "spotting" and shifting that is necessary in order to weigh, load, and unload the material hauled. For example, in the case of the locomotive hauling hot metal, the cars or ladles must be spotted for weighing three times on each round trip, in addition to three other stops,—two for loading and unloading, and the third for cleaning the ladle, this latter operation being performed on a spur leading off a *Y*.

In the case of the three locomotives hauling coarse concentrates, first-class ore, flue dust, slag, and limestone from the stock bins and brick plant to the blast furnaces, each carload must contain its proper proportion of each of the various ingredients, and each car must be “spotted" under the proper chute and weighed after each class of material is put in. At the other end, the train of from sixteen to twenty cars is moved back and forth eight or ten times in placing the various cars so that they can be unloaded in the proper place, in the proper furnace. Even the easiest runs involve at least two weighings of the train—one loaded and the other empty—and several shifts to place the cars at the proper points for loading and unloading. All this is necessary in order that the efficiency of the various operations may be traced at all times.

Samples of crude ore, concentrates, calcines, slags, flue dust and the metallic product of the blast and reverberatory furnaces, together with the black copper from the converter, are taken daily and analyzed. This combination of systematic weighing of all materials after every process, with daily sampling and analyses, enables the management to detect and stop promptly any unusual losses in the process.

To do this work, locomotives were required that were self-contained, reliable, powerful, smokeless, compact, and simple in operation. With steam locomotives the smoke and steam in the tunnels under the bins and furnaces would have made it almost impossible for the locomotive runner to see the signals. Electric locomotives would have required trolley wires or a third rail, either of which would have introduced serious difficulties in many locations too obvious to require explanation. Storage battery electric locomotives might have been used, but they are not adapted to severe and continuous service, and require too long a time for recharging the batteries or changing the cells.

When the reduction works were built, the engineers in charge decided in favour of compressed air locomotives as the best solution of the transportation problem. Their successors who now operate the plant apparently agree with them, as they have purchased additional compressed air locomotives, and have extended the system to cover movements of materials which the constructing engineers did not consider in connection with the original design. The writer heard but little criticism and much commendation. The general opinion of the operating force is thus summarized:—Under their conditions, compressed air locomotives are unsurpassed for convenience, reliability, and simplicity of operation.

Taking up the question of economy, the labour cost of operating the system is as low or lower than it would be with any other system. With them the cost of power is also extremely low as the steam is generated by waste heat from the reverberatory furnaces; but as the question of steam economy is of considerable interest under other conditions, and as an absolute determination was impossible under the circumstances, the writer will attempt a few comparisons, trusting that they may be found of interest.

During the month of April. the two compressors were operated continuously twenty-four hours a day, one at an average speed of 38.8 revolutions per minute; the other at 44.1 revolutions per minute. Under these conditions the total power developed would be 721 H. P. for both compressors, or an average of about 66 H. P. for each locomotive in operation. Ten out of the eleven locomotives in operation will develop 5700 pounds tractive force; the remaining locomotive will develop 9180 pounds. The speed is limited to 5 miles per hour.

Each one of the smaller locomotives would therefore be developing

$$\frac{5700 \times 5280 \times 5}{60 \times 33{,}000} = 76$$

horse-power at times; the large one

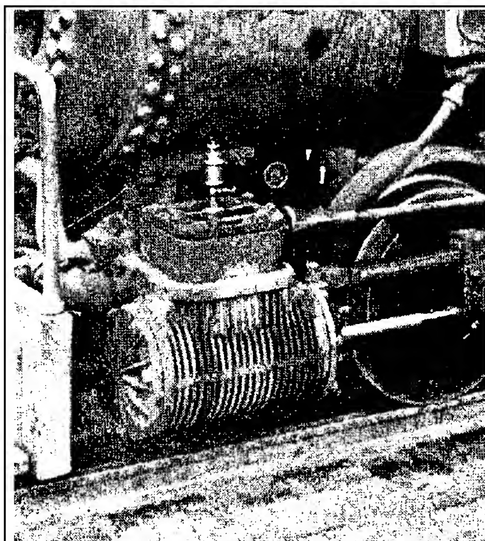
$$\frac{9180 \times 5280 \times 5}{60 \times 33{,}000} = 122$$

horse-power, giving a total of 76 × 10 = 760, added to 122 = 882 horsepower.

The approximate kilowatt input of an electric locomotive of the same weight as the smaller type of compressed air locomotive would be 95, and for the larger size 150; total, 95 × 10 = 950; l50 × l = 150; 950 + 150 = 1100 kilowatts.

If we assume that not more than one-half of the total rated capacity of the locomotives will be called for at any one time we have 550 kilowatts, or 550 × 1.34 = 737 electrical horsepower at the locomotives, to which must be added 5 per cent. for line losses,5 per cent. for dynamo losses. and about 7 per cent. for the friction of the engine; 737 × 1.17 = 862 for the indicated horse-power of the engine driving the dynamo to operate the same number and weight of electric locomotives with occasional overloads and the extreme fluctuations incident to the operation of electric locomotives. It does not seem, therefore, as though electric locomotives under the same conditions would be much more economical of steam.

As compared with steam locomotives, in order to make an intelligent comparison we must go back to the coal pile, even though the steam necessary to operate the compressed air locomotives at the reduction works is obtained from boilers that are run by waste heat.



Note the ribbed cylinders in the above close-up of the air engine

The two compressors, under normal conditions, required 323,100 pounds of steam per day of twenty-four hours. By referring to the table on page 471 [not shown] we see that there are thirty-one eight-hour locomotive shifts in each day of twenty-four hours. Assuming, for the sake of comparison, an evaporation of 7½ pounds of water per pound of coal, we find that to furnish steam for the compressors, 43,080 pounds of fair coal would be required, or, say, 1400 pounds of coal per compressed air locomotive shift. The writer has in his possession reports on the performance of twelve steam locomotives, having cylinders 9 inches in diameter by 14 inches stroke, which used from 760 to 2400 pounds of coal per day of ten hours, averaging about 1340 pounds.

Assuming that steam locomotives at the reduction works would use approximately the same quantity of fuel per hour, we have 1072 pounds for the small locomotives per shift, and 1500 pounds for the large one, giving a total of 1072 × 29 = 31,088. 1500 × 2 = 3000, 31,088 + 3000 = 34,088, or, say, 17 tons of coal for the steam locomotives doing the same work, as against 21½ tons for the compressed air locomotives

These calculations are, of course, nothing more than crude approximations, and are presented only as indicating that any change which might be effected in the cost of steam to operate the transportation system by substituting another form of motive power would be of minor importance when considered in connection with other expenses and the other desirable qualities of the existing system.

The cost of maintenance must certainly be less than with steam locomotives by about the amount necessary to wash out and keep in repair thirteen small locomotive boilers, as the cost of keeping the main storage tanks on the compressed air locomotives in repair has been nothing. The reremainder of the machinery of the compressed air locomotives being so nearly the same as that of the steam locomotive, there is no reason why there should be any difference in the cost of maintenance. The writer is of the opinion that the repairing of saddle tanks and the renewing of grate bars on steam locomotives would about balance any expenditure for maintenance of a stationary plant, including the boilers.

In comparing the cost of maintenance with electric locomotives no such direct deductions are possible. The machinery is radically different and the friends of both systems claim superiority in this respect for their favourites. With the electric locomotives, dust and dirt are more easily kept away from the wearing parts; but the same casing that keeps out the dust prevents the free circulation of air around the armature and commutator, and renders them more liable to injury from overheating. So little reliable data is to be had that it is all a matter of opinion. Figures have been published showing that compressed air locomotives are more economical to maintain than are electric locomotives, but there are no detailed and reliable figures to show electric locomotives more economical than compressed air locomotives.

One set of figures, however, does not settle the matter. Probably local conditions and designs have more to do with the relative cost of maintenance than any inherent qualities of the two systems. Compressed air locomotives have this advantage: charge after charge of air may be used in quick succession, with the locomotive working at all times at full capacity without injury. This is not true of electric locomotives. The electric motors which drive the locomotives are so designed that they can be run for one hour at rated draw-bar pull and speed without injurious heating, provided the motors are started cold. As a rule this provision is sufficient, but occasionally it is not, and a burnout occurs.

The problem of internal transportation in many large establishments is a serious one, and during the writer's stay at Anaconda the many advantages of compressed air locomotives for such service were so manifest. and the evidence that their development had reached a stage justifying the confidence of engineers and business men was so conclusive, that a brief account of what was being accomplished with this form of motive power seemed of general interest.

Compressed air locomotives, however have their limitations. They are not intended for long continuous runs in one direction, and their efficiency would be relatively low where starts and stops were infrequent; but for service conditions similar to those existing at the Anaconda Copper Mining Company's new reduction works there would seem to be a wide field of usefulness, more especially where waste heat from heating or blast furnaces, or the refuse from woodworking establishments, or water power, could be

utilized to operate the compressor, thus saving the fuel necessary to operate steam locomotives, doing away with trolley wires, and eliminating all risk of fire.

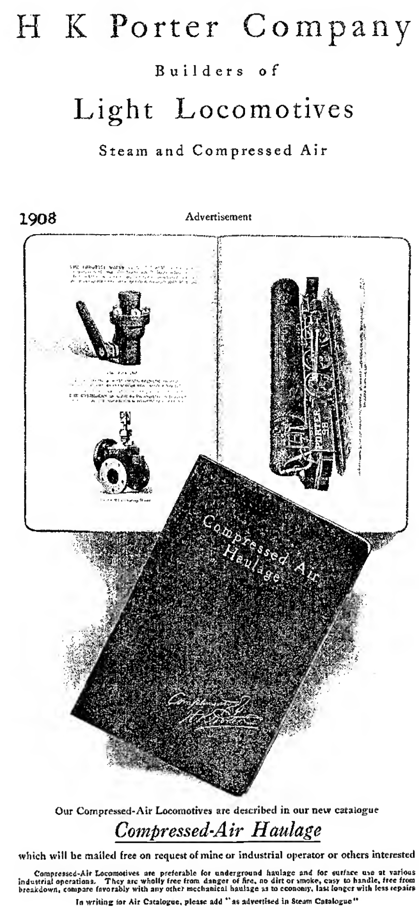
<u>Compressed Air Haulage, System of H. K. Porter Company</u>, trade catalog, Pittsburgh: H. K. Porter, 1908, p. 1-15

Compressed Air Haulage

As Installed by

H. K. Porter Company Pittsburgh Pa

Compressed air locomotives were first built by H. K Porter & Company in 1890. The original firm to which the H. K. Porter Company is successor began building light steam locomotives in 1866. These early compressed air locomotives were crude in many respects, but many of them are still running regularly and doing good work. In 1895 compressed air locomotives were built having all the essential features of our most recent productions. Since that time many practical improvements in details have been made, among which may be mentioned an increased pressure in the main storage tanks, and an improved type of automatic reducing and stop valve for maintaining a uniform pressure at the throttle valve. Not only the locomotive, but the compressor, pipe line, charging stations, valves and fittings have all been subjected to a most searching scrutiny, with a view to eliminating any defects which experience has developed The Ingersoll-Sergeant Drill Company and The Norwalk Iron Works Company are to-day building compressors for pressures as high as 600 to 2,500 pounds per square inch, with the same certainty of obtaining the desired results as in any other department of their business. The governing devices, valves, lubricators, intercoolers, water jackets and all other details have been gradually improved in the light of past experience. We are therefore exceptionally well prepared to submit estimates for complete installations, including compressed air locomotives, charging stations, pipe line or other system of stationary storage, and compressor, and to state the amount of steam or other power which may be required We offer to our customers the advantage of dealing with one competent concern which stands behind the entire equipment, ready not only to replace within a reasonable time any parts which shall show defects other than those due to ordinary wear and tear and carelessness in handling, but also to guarantee an installation well proportioned in all its details and fully up to the required capacity. Having built about four times as many compressed air locomotives as any other builder, we have been justified in making greater expenditures in



equipping our shops with special tools, and of giving our engineers special training for this class of work Special tools mean good workmanship at minimum cost. Experienced engineers insure proper materials, good designs and successful adaptation of means to ends The demand for compressed air locomotives has been so far beyond our most sanguine expectations that we have again been compelled greatly to increase our facilities. In view of the practical results already obtained, we feel justified in claiming that the compressed air locomotive has passed the experimental stage and now stands as one of the well established means for the transportation of materials in and about industrial works and mines of all descriptions. We urge our customers to satisfy themselves in regard to our equipment by inspecting our past installations, and by examining the locomotives under construction in our shops and the systems and methods there employed. The more thorough your examination of all the • various systems of haulage including our own the better we consider will be our chances of obtaining your business.

The demand for compressed air locomotives has been so far beyond our most sanguine expectations that we have again been compelled greatly to increase our facilities. In view of the practical results already obtained, we feel justified in claiming that the compressed air locomotive has passed the experimental stage and now stands as one of the well established means for...transportation...

The Field for the Compressed Air Locomotive

We have obtained most satisfactory results with compressed air locomotives under a great variety of conditions. We have built them for gauges of track varying from 18 to 56½ inches, for grades from level up to 10 per cent, for curves as sharp as 15 feet radius, and for trains varying from a few thousand pounds to four or five hundred tons, and for hauls varying from a few hundred feet up to three miles. Our underground installations include haulage plants for anthracite and bituminous coal mines both gaseous and non gaseous: for main haulage work with heavy trains, and also for the lighter work of gathering coal from the working faces in single cars and light trains. For surface work we have installed our locomotive not only in places where a reduction of the fire risk was an important consideration as at woodworking plants, lumber yards, magazines for storage of explosives, and powder yards, but also at points where the fire risk introduced by the use of steam or electric locomotives was unimportant and where compressed air locomotives were adopted because of their general utility, economy, and reliability, as for instance at malleable iron works, gas works, copper reduction works, and mills for the refining of precious metals.

The above statements serve to indicate what has been done, but we feel that the field of the compressed air locomotive is capable of being still further extended, and that as it becomes better known to the engineering world its use will become more and more general. Our installations include small plants with single locomotives, and larger plants with from six to thirteen locomotives operated from one central power station. We have installed them at coal mines where fuel was a secondary consideration and the crudest type of steam engine was used to drive the compressor, and at points in the far West where fuel

was very expensive and the highest type of compound condensing engine was used for the generation of power.

Essential Features of a Compressed Air Haulage Plant

1. One or more compressed air locomotives, proper design and capacity to suit the conditions.
2. One or more air compressors of sufficient capacity.
3. One or more charging stations.
4. A storage system (usually a pipe line) of suitable capacity and properly designed to admit of placing charging stations at convenient points.
5. Last and most important, all parts must he properly combined to form a satisfactory working plant as a whole.

Some Advantages of Air Haulage

RELIABILITY.—A haulage system that can be depended upon to work all day and every day in the hands of workmen of ordinary ability, is a reliable system. Other qualities are desirable, but reliability is a necessity. In developing our system of haulage by compressed air locomotives we have kept the vital importance of this quality constantly in mind, and have never lost sight of it in our efforts to reduce the selling price and secure a high mechanical efficiency.

Persons not practically familiar with air haulage frequently have the impression that serious difficulty is to be anticipated from freezing in the exhaust passages of the locomotive. Compressed air locomotives have been used for thirteen years, and no such difficulty has developed This difficulty is suggested by the freezing which frequently occurs when air is used at lower pressures. With the higher pressures used in connection with locomotives this difficulty is eliminated, as practically all of the moisture is squeezed out of the air in the process of compression and deposited in the stationary storage or in the tanks on the locomotive, where it can be drawn off at convenient times. The outside of the locomotive cylinders and valve chests becomes cold and frequently coated with frost, and the exhaust, when it comes in contact with the outside air, condenses moisture in it, producing an appearance similar to that of low-pressure steam, which almost immediately disappears; but there is no moisture in the working parts of a compressed air locomotive, and if a suitable oil is used there is nothing inside the locomotive which can be frozen.

As compared with all other systems, the machinery of a compressed air haulage plant is simple, strong and accessible, with the power limited by the design, and hence capable of being worked up to its full limit without danger of breakage or liability to the frequent temporary delays which are so annoying in connection with the operation of many of its competitors

ADAPTABILITY—Compressed air locomotives are more easily operated than steam locomotives, as the skill necessary to preserve a steam boiler in proper condition is entirely eliminated. Compressed air locomotives are an everyday working success, with all the good features of the electric storage battery locomotives, and some others of their own, in that the tanks do not deteriorate as the batteries do, are not injured by shocks or excessive demands for power; they are compact, and can be built to conform to any ordinary limitations of height and width, as, for instance, in any place where mules can be

used. Our compressed air locomotives are capable of running from 3,000 to 15,000 feet with one charge of air. These distances may be more than doubled by the use of a tender carrying an additional supply of air. A locomotive can easily be charged in from one to two minutes, and with charging stations located at convenient points, the radius of action for the locomotive with one charge of air is abundantly large for mining and industrial service, and there are no overhead or underfoot obstructions corresponding to the trolley wires of the electric system or sheaves of rope haulage.

These features make compressed air locomotives exceedingly convenient for industrial service in mills and manufactories where traveling cranes, belts and other machinery render the location of the trolley wires for electric haulage very difficult. The fact that compressed air locomotives carry a considerable supply of energy with them makes this system the ideal haulage for gathering coal from the working faces in mines, and it is, in our opinion, the only mechanical power that can do this work successfully. The experiments with storage battery electric locomotives in this service have not been very encouraging, and the "cable-reel" device to the mechanical mind, seems very much in the nature of a makeshift. The compressed air locomotive will run wherever rails are laid, and will operate successfully on steeper grades than are practicable with steam or electric locomotives. Moreover, they may be worked for an indefinite length of time up to their full capacity without danger of injury, which is not true of the electric locomotive, as all electric locomotives are built with motors which depend for their continued existence upon frequent periods of rest in which to cool off.

Repair Accounts and Operating Expenses

The repair account of a compressed air locomotive is less than that of a steam locomotive, since all the boiler repairs of a steam locomotive are eliminated. This, combined with the less expensive men required to run them, has been a sufficient reason for the adoption of compressed air locomotives where a number were to be operated from one central power station. A comparison of the cost of repairs for compressed air locomotives and electric locomotives is decidedly in favor of the air. (This matter is treated more fully a little further on.) As compared with rope haulage, it is nearly always less, but the life of rope and sheaves is so dependent upon the straightness of the haul and upon atmospheric and other conditions that any general comparison is impossible.

> As a matter of history, an examination of the records shows no deaths or injuries which can be in any way attributed to defects or weaknesses of this system. There are at the present time between 50 and 75 air haulage plants, each with one to thirteen of our air locomotives in everyday service, so that our claim that air haulage is safe is based upon a considerable mass of evidence.

The cost of operatives (locomotive runners and trainmen) for compressed air locomotives is lower than for any other system. It is a mistake to trust good machinery of any sort to ignorant or careless men, but high-priced expert labor is unnecessary in connection with the air locomotive. Experience has proved that where mules are replaced by our air locomotives, it does not take long for a mule driver to become a satisfactory locomotive runner.

The compressor is self-regulating

and runs at moderate speeds, so that the man in charge can easily attend to other duties in the same or adjacent buildings. The compressor is not subjected to the variations of load so troublesome in connection with the operation of the generator for electric haulage, as the locomotives when in operation are independent of the compressor, and there may be one or ten charged by one compressor, and yet by virtue of their independent action after charging all can be starting heavy trains at the same instant without in any way affecting the continuous operation of the plant. Compare this statement with the following quotation taken from an article written for one of the prominent mining journals by a gentleman identified with one of the largest manufacturers of electric locomotives in the United States.

"Annoying delays are often experienced at mine haulage plants where there are several locomotives, due to the frequent 'blowing' of the circuit breakers. It is proper, of course, that the circuits should be automatically opened when the generator is called upon to deliver a current beyond its safe capacity, but it is annoying if the service is interrupted with too great frequency. The remedy for this trouble also lies, to a very great extent, in the hands of the motorman, as the intelligent use of the controller will minimize the demand upon the generator. This trouble is aggravated by the simultaneous starting of all of the locomotives when the circuit breaker is reset by the engineer at the power house, since each locomotive requires a comparatively large current when starting, and the sum of their starting currents is often sufficient to immediately blow the circuit breaker again. In this way it often happens that the entire haulage system may be interrupted for a half hour or more. The engineer occasionally becomes righteously indignant, allows the circuit breaker to remain out a few moments before resetting it and the relations between the employes of the power house and the motormen become strained, with no good results to the company."

Safety

The economy, adaptability and reliability of air haulage deserve due weight in the choice of a haulage system, but under many conditions the positive safety of a compressed air locomotive, as compared with any known form of motive power, should be decisively in its favor. As a matter of history, an examination of the records shows no deaths or injuries which can be in any way attributed to defects or weaknesses of this system. There are at the present time between 50 and 75 air haulage plants, each with one to thirteen of our air locomotives in everyday service, so that our claim that air haulage is safe is based upon a considerable mass of evidence. The high pressures used in connection with this system may seem to the uninitiated rather dangerous; but if the same factor of safety be maintained for 800 to 1000 pounds pressure as is maintained with 80 or 100 pounds pressure, and if in addition the material used is not subjected to the injurious influences of fire, scale and corrosion, there is no reason why 800 to 1000 pounds should not be as safe as 80 or 100 pounds and the result of an explosion with 800 to 1000 pounds of air is not as dangerous as would be the case with 100 to 150 pounds of steam, as the air may bruise but it will not scald. If electric haulage could be made as safe as air haulage, or if air haulage had resulted in one-quarter as many deaths as has electric haulage, we feel certain that the facts would have been most thoroughly ventilated in the engineering and mining press. Even as it is, the claim is set up that while contact with an electric wire carrying 500

volts may sometimes be fatal to horses and mules, it is not fatal to men. The official records, however, show that this statement is unquestionably false, and conservative managers are now insisting upon a maximum limit of not over 300 volts wherever naked wires are to be employed with which men may accidentally come in contact. During four years, in ten collieries—mostly operated by one company—and all in one district of one State, eighteen men were killed by the electric shock. We have no data as to how many men during the same time may have come in contact with the wires and escaped with their lives.

Electric wires and machinery above ground, and more particularly under ground, are liable to derangements which may easily develop enough heat to start destructive fires. It would be difficult to overestimate the losses within the past few years due to this cause. Electric sparks, either from the trolley or at the commutator, will set fire to mine gas just as quickly and certainly as would the flame of a lamp or match. The statement has been made that more fires have been started by miners disobeying orders than have been started by electric apparatus, and doubtless this is true; but it would be a very reckless mine operator who would use the presence of one danger as a justification of neglect to remove another danger.

In closing the discussion of this feature of compressed air locomotives, we make the following brief quotations from the report of the Bureau of Mines, Department of Internal Affairs of Pennsylvania, for the year 1899, page XIII:

"Besides the increased danger from explosive gases, other elements of danger have been introduced into the mines by the use of mining machines and electricity. These have been introduced during the past ten years, and it is the opinion of the writer that the use of electricity in any form in coal mines is a menace to life, limb and property."

In the report of the same Bureau of Mines for the year 1901, on page 3:

"Electricity is one cause of fatalities in the bituminous mines (seven having lost their fives through it in 1901) that so far has not proved fatal to any person in the anthracite mines. Electricity in various forms has been the cause of many deaths in the soft coal mines, either from the men coming in contact with the electric trolley wire or with the electric wire that carries the power to the electric cutting machines. In my opinion separate traveling ways should be provided for the workmen when the haulage is done by electricity, unless the wires can be raised to a distance of at least six feet from the rail, and even then there should be sufficient room for passing on the main haulage roads at all points, as men cannot always reach the the 'safety holes' in time. In every case where electric machines are used for cutting coal, the wires should be made absolutely safe, as men in the hurry of their work forget about the 'deadly wire,' touch it, and all is over, and the report follows, 'killed by an electric shock.' Humanity demands protection for the workingmen from this most deadly agent recently introduced and employed in the coal mines. I hope the time will come when 'compressed air,' 'liquid air,' or some other agent will supplant electricity in coal mines, but this will not take place until the necessary power can be generated as cheaply as by electricity. In gaseous mines electric cutting machines or electric motors should never be permitted in use, as otherwise sooner or later they will be the cause of a great catastrophe."

In the report of the same Bureau of Mines for the year 1902, on page 4:

"Again I wish to enter my solemn protest against the use of electricity in the coal mines of this State, unless wires can be so protected as to prevent its being a menace to life. Had I authority, I would prohibit its use in any form in gaseous mines, as it is my firm belief, if the use of it is not prohibited, that sooner or later there will be a terrible loss of life from this cause. Seven lives were lost from this cause in 1902 and the same number in 1901, making fourteen lives sacrificed from the use of this deadly agent in two years. This adds to the great number of perils incident to the mining of coal."

Other extracts could be made from the reports of the Bureau of Mines for the above and other years, which give frequent instances of deaths caused by electricity. The mine inspectors of the various districts are competent men, with no reason for condemning electricity or favoring compressed air, other than their observation of the two systems in operation.

As a contrast to the dangers of electricity, no accident was reported from the use of compressed air. On the contrary, a number of instances are cited where the presence of compressed air has been the means of preserving life. In mine explosions as many lives are lost as the result of "afterdamp" as are lost at the time of the explosion itself. The explosions frequently cause falls, which cut off the miners from the shaft, slope or other exit from the mine, and it is in these cases that the pipes have been instrumental in saving life, the miners either opening the valves or breaking the pipes to obtain a supply of fresh air, which could not reach them in any other way. The air pipes may also be used to carry water in case of fire, thus avoiding the delay incident to laying special lines to get the water where it is required.

An electric motor is an inefficient machine while coming up to normal speed; a steam engine is inefficient until the walls of the cylinders are thoroughly heated; but a compressed air engine is most efficient, thermodynamically, with the first movement of the piston, because the walls of the cylinders are then at their highest temperature. This fact would point to the use of compressed air locomotives wherever stops and starts are to occur with great frequency.

U. S. Patent No. 868,560, Interheater for Compound Compressed-Air Engines, Patented October 15, 1907, by Charles B. Hodges of Pittsburgh, Pennsyvania. The French three-stage design beginning on the next page was based on Hodges' patent, but takes it a few steps further; heat was absorbed before all three stages, and regenerative braking was incorporated to add compressed air and heat to the tanks and interheater.

1920 BULLETIN of the SOCIETY of the MINERAL INDUSTRY

(BULLETIN de la SOCIÉTÉ DE L'INDUSTRIE MINÉRALE)

A STUDY OF TRIPLE EXPANSION COMPRESSED AIR LOCOMOTIVES (preliminary computer translation by Scott Robertson)

and

The UTILIZATION of EXHAUST STEAM For The Production of High Pressure Air (not included in this translation)

by Mr. P. E. LEROUX, Engineer of the Crafts and Professions.

The fast removal of the products of working the mine must come to the attention of the operators of collieries more and more, for it is intimately linked to the question of labor underground.

Given its scarcity, the extraordinary elevation of its cost price and the limitation of the mining season, it is absolute necessary to resort to mechanical means.

Underground transportation by locomotives, which began to become popular in our mines before the war, will soon become the norm.

Without regress to the advantages and disadvantages of the various means of traction employed, we could say that in the coal mines the compressed air locomotive is the only one that could be adopted without any danger and with the greater economy.

Until this era the locomotives had not yet completely replaced the use of horses underground. We think that it could possibly succeed by installing in the front of the locomotive a small winch with a rotary motor, the dolly of which could accommodate 200 to 300 meters of cable made of very flexible steel from 6 to 8 mm diameter, with coupling link and automatic brake capable of a tractive effort of 300 to 350 kilograms and controlled from the cab of mechanic.

In the underground locomotives, the power plant must be easily accessible; its position between the beams or inside, obliges the mechanic to leave his cab for trifling repairs and often requires pit stops.

Given the light gauge of the rail and the reduced work area from the size of the machines the cylinders disposed either to the interior or to the exterior of the side-beams, with a relatively small diameter which doesn't permit the multiple expansions in series of the diameters as they are designed.

Our new locomotive was designed in order to prevent these inconveniences and reduce as much as possible the consumption of air and the expense of upkeep.

The interchangeability of motor, as well as the accessibility of all the parts even while en route, allows easiest overhauling; and its reassembly by daylight, leaving the chassis part and tanks underground, which used so much work space as to make the reassembly maneuver often laborious and very expensive.

The use of triple expansion reduces the consumption of air to the

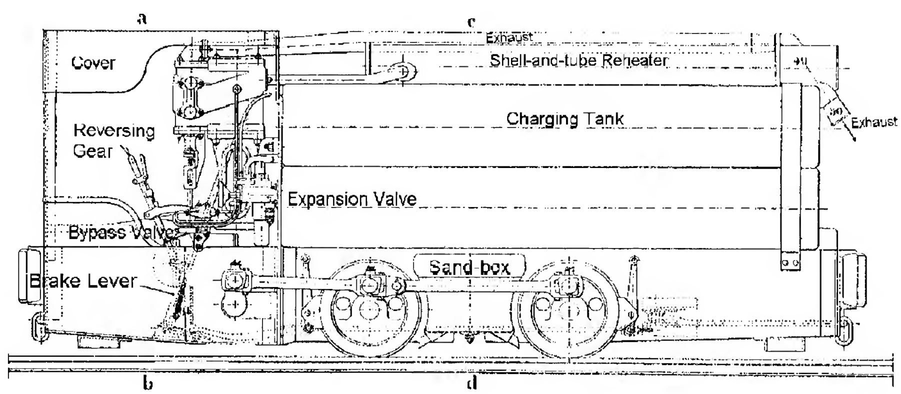


Fig. 1. Elevation

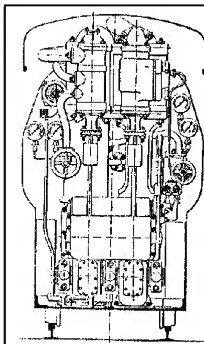


Fig. 2: Section A B

minimum. The regenerative braking which occurs by running the engine as a compressor, allows the use of the resistance work, by means of the production of compressed air and amassing heat in the shell-and-tube heat exchangers inserted between each expansion.

After stopping, the next startup proceeds from the most advantageous conditions, since there exists a slight excess of pressure in the drive tank and an excess of heat energy in the intermediate tanks.

Our locomotive starts under full load, from all crank positions, because besides the advantages above-mentioned, we provided a bypass apparatus, allowing us to send some of the air of high pressure into the intermediate tanks.

It comprises a chassis made of sheet steel, of which the rear part, forming the driver's stand, can be dismantled very quickly in order to allow the removal of the engine. (Fig. 1-2-3-4).

The chassis rests on two straight driving axles, by way of four leaf springs, arranged so as to uniformly distribute the stresses of reaction by a reasonable absorption of the shocks.

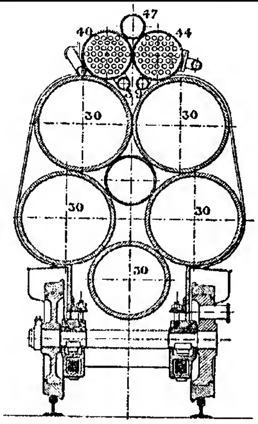


Fig. 3: Section C D

The wheels are keyed on the axles; they are made up of a body of case-hardened cast iron, with tires made of hard steel, laminated without

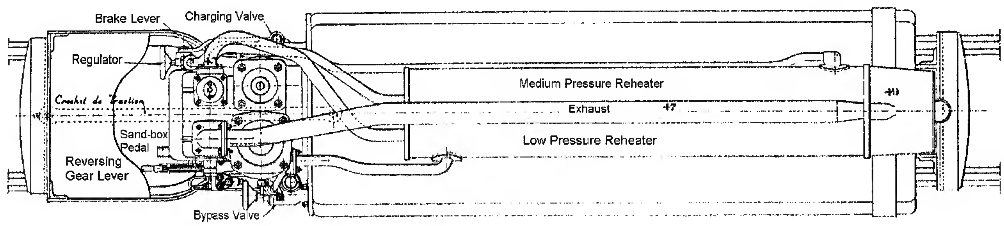


Fig. 4: Plan View

welding, of a thickness amply sufficient to endure several re-turnings after wear in service.

The wheels are joined to each other by the coupling rods.

The upper part of the chassis accommodates up to five supply tanks. They are constructed of mild steel with a resistance from 35 to 40 kg per mm^2 of section for an elongation of 25%; they communicate among themselves by suitable coupling and the whole is tested to a pressure of 225 kg/cm^2, corresponding to a maximum working pressure of 150 kg.

The tanks are securely attached to the chassis' rear support, made of iron plate; this support accommodates the engine also.

This last is of the vertical type and comprises two parallel cylinders (Fig 5-6-7). The first is a differential piston; part (1) forms the high pressure cylinder; part (2) the medium pressure. The second cylinder (3) is the low pressure cylinder with double-acting piston.

The length of the high pressure piston assures flawless guiding and allows multiple piston rings so as to obtain a great tightness while eliminating the inconveniences of a stuffing-box. On this piston is articulated at (5) the connecting-rod (5-6).

The low pressure piston is of the "Swedish" type (Fig. 5).

The guide is cylindrical, the crosshead 7 is provided with large blocks, and the connecting-rod 7-8 is identical to the rod 5-6; the crank-end ("head"-end) and "foot"-end connecting-rod bearings are for taking-up of play.

The engine shaft, made of forged treated steel, is supported by three bearings, which serves to obtain the maximum of strength with an appreciable reduction in size of the journals. The two cranks transmitting the motion from the shaft to the two axles came from the forge with the aforesaid shaft.

The valve-gear (patented S. G. D. G.) has no eccentric, which appreciably decreases the space taken up by the engine, while reducing to a minimum the number of parts.

It comprises (Fig. 5-6-7) a rod 9-10 articulated at 9 on the connecting-rod and at 10 on a slide-block moving in a cylindrical guide.

On this rod at 11, is articulated the lever (11-12) of which the end (12) carries a slide-block moving on the slide (13-14). At 22 on the lever 12/11 is articulated the slide-valve control rod (22-23) of the valve-gear.

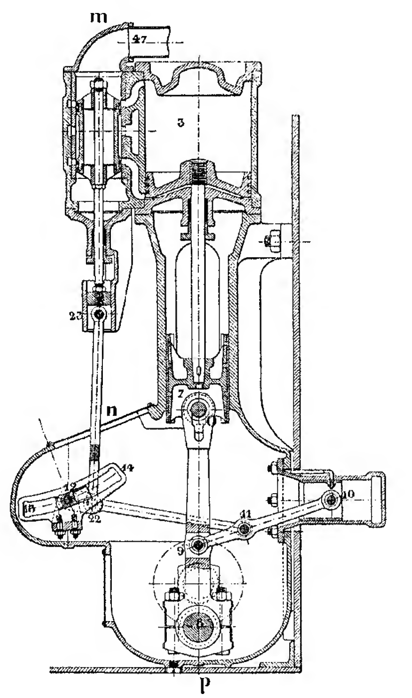


Fig. 5: Section I J

Each slide-valve includes an identical valve-gear. The two slides are attached (Fig. 6) on a handle which is raised (15-16-17) to select the various positions of the slide; pivoting with this shaft enables the variation of expansion as well as the reversing of operation.

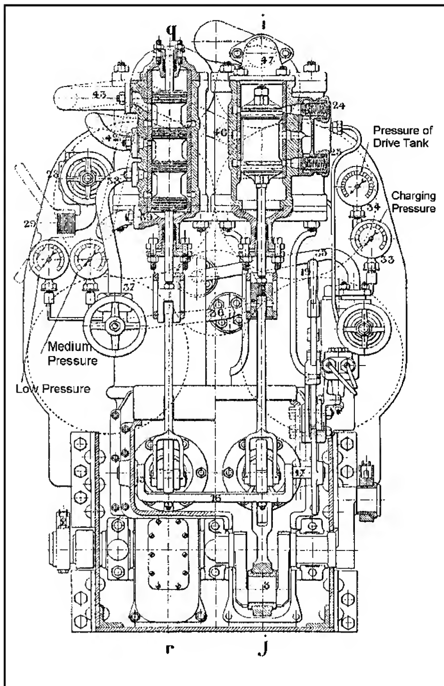


Fig. 6: Section K L
Section M N O P

The shaft is controlled by the lever of the reversing gear (18/19) which moves over a notched sector (20-21) in which it could be set in any position by a stop block provided with a compression spring.

With inexpensive parts of very great simplicity, this arrangement achieves running with variable expansion and makes it possible to have identical phases in the two directions of operation. The precision in the valve-gear is comparable to that of the perfected steam locomotives.

On each valve box (Fig. 6 and 7) are mounted the discharge valves: (24 and 25) for the low pressure cylinder, (26) for the medium pressure cylinder and 27 for the high pressure cylinder.

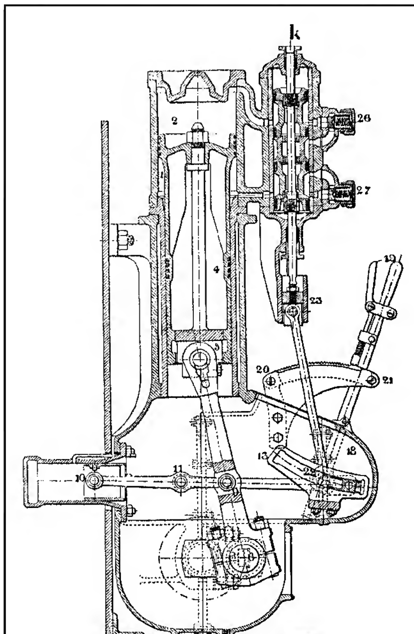


Fig. 7: Section Q R

These valves in normal operation are closed automatically by the pressure of the air from the tank supplying the corresponding cylinder. They open as soon as the pressure of compression in the cylinder overcomes the pressure existing in the tank (counteracting).

The charging of the locomotive (Fig. 6) proceeds via a valve (28) connected to the high pressure pipe by a flexible pipe provided with a coupling threaded to the handle (29).

This charging valve is provided with a check valve which prevents the loss of the compressed air into the atmosphere, if, by oversight, someone undid the coupling before closing the valve.

At (32) is attached a pressure-reducing valve provided with a safety valve and with a pressure gauge (33).

BYPASS STARTER

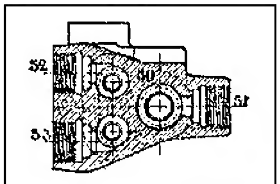


Fig. 8: Section G H

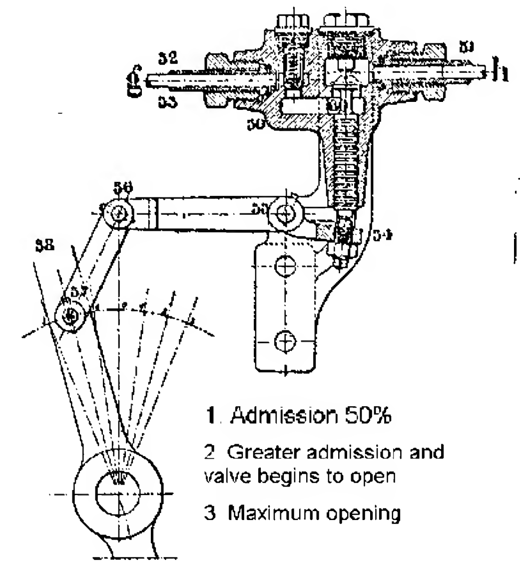


Fig. 9: Section E F

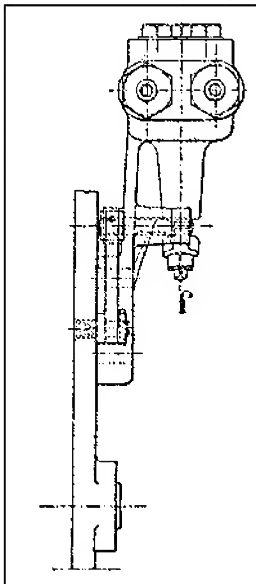


Fig. 10: Profile

The pressure-reducing valve takes the compressed air at the pressure of the tanks and brings it to the drive tank with which it communicates via the hose (35).

The engine air taken from the drive tank via the hose (36) passes through the throttle valve (37) in order to arrive at the admission of the high pressure cylinder at 38.

After having worked upon the annular face of the high pressure piston, the air escapes at 39 and presents itself (Fig. 3) to the interheater (40) from where it is taken via a hose (41) and brought at (42) to the medium pressure admission; then escapes (Fig. 4 and 6) at (43) in order to surrender to the second interheater (44) (Fig. 3) and from there to the admission (Fig. 6) of low pressure cylinder, at (46), and after expansion escapes at (47).

DETAILS OF THE EXHAUST-DRIVEN JET PUMP

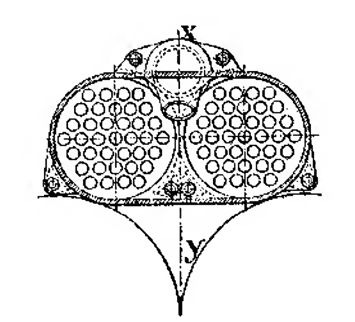


Fig. 11: Section S T U V

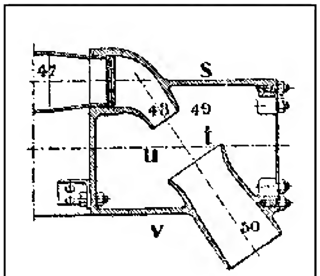


Fig. 12: Section X Y

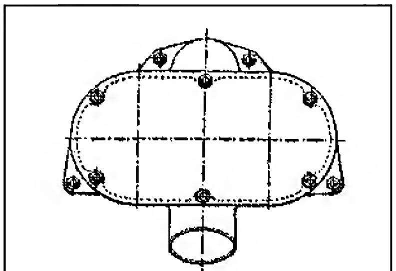


Fig. 13: Front view

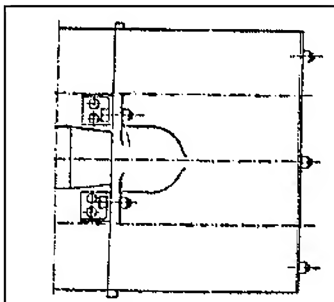


Fig. 14: Plan view

The exhaust (47) proceeds (Fig. 11-12-13-14) through a nozzle (48) in a horn (50), creating a suction in a chamber made of cast iron (49) attached in front of the tubular bundle in the interheater.

The outside entrained atmosphere passes through the interior of the tubes and warms the air circulating among the tubes by contact.

When the locomotive is in operation, and one wants to bring it to a stop, one moves the lever of the reversing gear backwards, which brings about the operation of the engine as a compressor; the air is drawn in through the exhaust of the

low pressure cylinder, then compressed following the different stages of admission, then discharged without any cooling, into the interheaters, then into the drive tank, greatly warming each one of these vessels.

The drive tank and the two reheaters are provided with safety valves adjusted for working at pressures a little higher than the normal. If, in this reversal of operation, the pressures obtained in the tanks go beyond those for which the valves are adjusted, they open and vent air; but the mass of the tanks have stored a quite substantial quantity of heat that will be recovered.

On account of the opposing work developed, the machine doesn't hesitate to come to a stop, and in case of necessity only, one could get the same result braking with the conventional lever and shoes, after the first maneuver of the reversing gear lever, when bringing it back to the middle point of the toothed sector (20-21) after stopping.

We recover thus in compressed air and in heat stored in the metallic mass of the shell-and-tube, a part of the energy which was once totally lost with the brakes on the engine's wheels, which improves the output of the locomotive appreciably, as examination of the diagrams would substantiate.

In order to set the locomotive in operation it was sufficient to move the lever of the reversing gear in the desired direction, until in the last notch-stop of the sector. If the machine, because of an unfavorable position of the cranks, doesn't start, one continues to move the lever, and, then, one enters into action the bypass starter.

The latter (Fig. 8-9-10) comprises a body made of bronze (50) in communication by the nozzle (51) with the drive tank and by (52 and 53) with the chambers of admission of the medium and low pressure engine cylinders.

The nozzles (52 and 53) are provided with check valves and their communication with (51) is obtained by the rising of valve (60). This valve is controlled by the lever (54-56) oscillating around an axis (55) fixed to a support having come from the foundry with an attachment flange on the body of the bypass starter.

This lever is manipulated by a small rod (56-57) articulated at (57) on the lever of the reversing gear (59-58).

The bypass starter enters into action only when the lever of the reversing gear is at point (2) of the sector, corresponding to the greatest normal admission.

Further displacement from (2) to (3) for each direction of operation, corresponds to an admission which could go beyond 90%; at the same time the valve (60) opens, permitting the direct feeding of the interheaters.

The maximum torque is reached and the locomotive moves off; further displacement of the lever requires a supplement of effort from the driver; as soon as the locomotive is started the latter releases his lever intuitively, which, encouraged by the response of the valve-gear and by the action of coil spring (61) (Fig. 1) returns to the first notch-stop which yields the maximum admission in normal operation.

In bringing back the lever more closely to the middle position, one gives the admission the appropriate value.

The whole of the engine and the different parts are very accessible without any inconvenience to the mechanic driver.

The moving parts and those of the valve-gear are thoroughly sheltered in a weatherproof cover.

Study of a triple expansion locomotive with regenerative braking.

The recognized features are the following:

Weight of the machine ready to operate,	6,500 kg.
Useful volume of locomotive tanks,	1,300 liters.
Filling pressure of the tanks,	150 kg/cm^2.
Residual pressure at end of operation,	28-30 kg.
Diameter of differential piston,	160-195 mm.
Diameter of low pressure piston,	245 mm.
Common stroke of the pistons,	210 mm.
Diameter of the car wheels,	0.5 mm.
Max. pressure admitted to high pressure cyl.,	30 kg/cm^2.

We have taken pains to design our engine with respect to the Laws of Thermodynamics as much as possible. In the construction of heat engines one must obtain the fast opening and closing of the intake and exhaust valves, especially with those of compressed air; to this end people have imagined a great number of systems of very complicated gadgets that wear quickly and are very expensive maintenance. Our valve-gear as previously described allows us to obtain very simply the benefit of speed without the inconveniences and the frailty of the apparatuses known until now.

We won't return to the description already previously made, but go only into a study of the different valve events.

The axis 9 (Fig. 20 and 21) describes an elliptic curve of which the length of the large axis is equal to the stroke of the piston, and the small axis varies according to the position of a point on the crank-arm.

In order to reduce the travel of the slide-valves and to make the valve-gear work the same in both directions of operation A V and A R, we have (Fig. 5-6-7-20 and 21) provided a lever 9-10 on which is articulated the control lever of slide-valve 11-12; in which the point 11 describes a curve varying according to its position on the lever 9-10; its width increases when the point 11 draws nearer to 9 and decreases in drawing nearer to point 10.

On account of the successive displacements of point 12 in the course of the sector forming slide-shaft 13-14, the point 22 describes a curve of which the slope varies according to the position of sector slide-shaft 13-14, which makes the reversing gear work according to whether one places the slide-shaft in one direction or in the other.

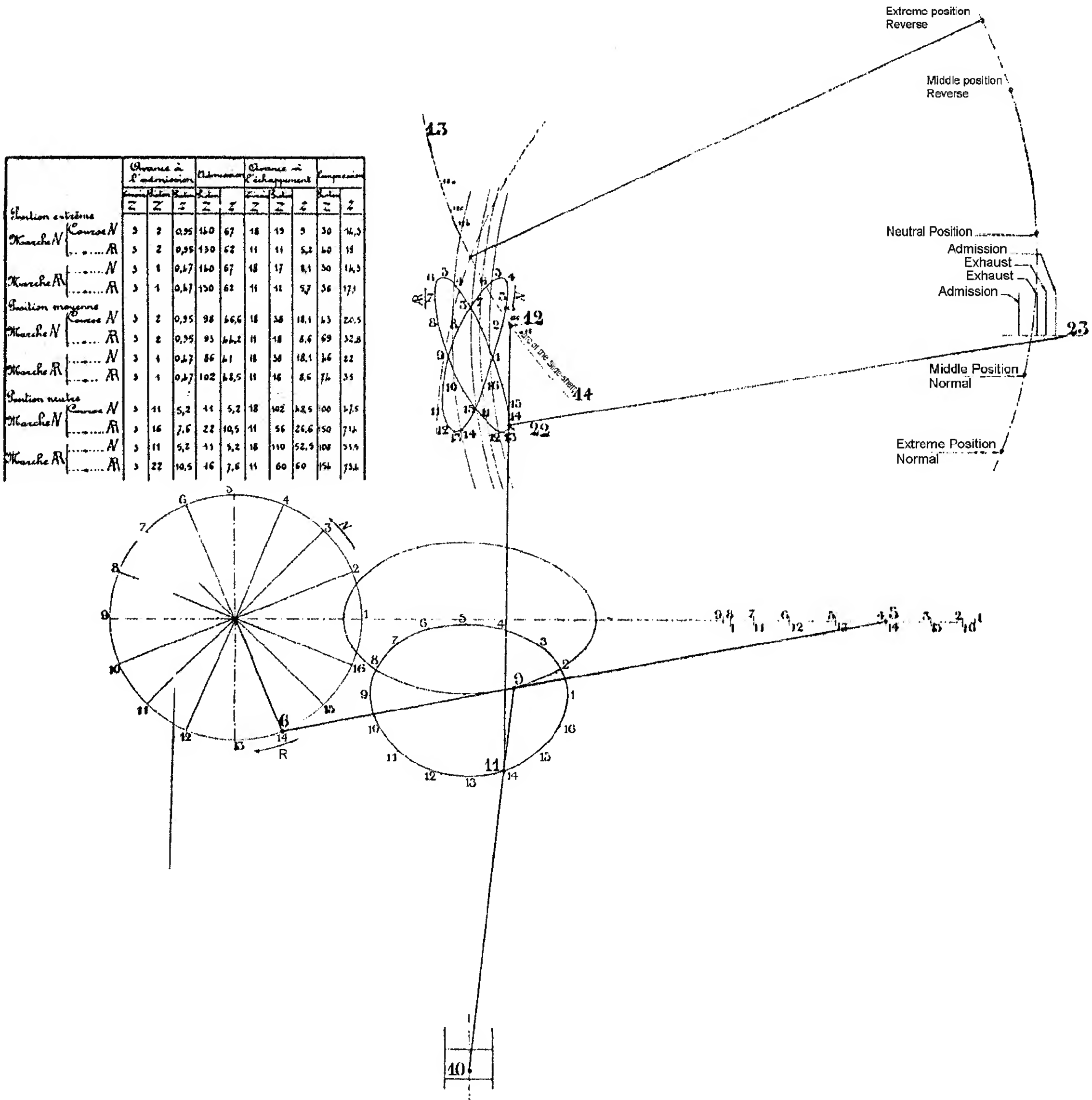
Just as one moves the point 9 away from the points 6 or 8 and just as one increases the distances 12-22 and 10-11 with regard to 11-22 and 9-11, so the travel of the slide-valve increases; in varying these different positions and lengths one modifies the phases of the valve gear.

Plotting of the valve-gear (Fig. 20 and 21).

We restrict ourselves to an admission from 60 to 65% of the stroke of the piston.

We plot our slide-valve and also make the point 9 as near as possible to the crank in order to reduce the thickness or breadth of the curve described by the point 22, and in order to reduce the travel of the slide-valve.

VALVE GEAR DIAGRAMS AND A STUDY OF THE WORK DEVELOPED
(Diagrams continue on the following pages--editor)



		Avance à l'admission			Admission		Avance à l'échappement			Compression	
		%	%	%	%	%	%	%	%	%	%
Position extrême											
Marche N	Course N	3	2	0,95	140	67	18	19	9	30	14,3
	...R	3	2	0,95	130	62	11	11	5,2	40	19
Marche R	...N	3	1	0,47	140	67	18	17	8,1	30	14,3
	...R	3	1	0,47	130	62	11	12	5,7	36	17,1
Position moyenne											
Marche N	Course N	3	2	0,95	98	46,6	18	38	18,1	43	20,5
	...R	3	2	0,95	93	44,2	11	18	8,6	69	32,8
Marche R	...N	3	1	0,47	86	41	18	38	18,1	46	22
	...R	3	1	0,47	102	48,5	11	18	8,6	74	35
Position neutre											
Marche N	Course N	3	11	5,2	11	5,2	18	102	48,5	100	47,5
	...R	3	16	7,6	22	10,5	11	56	26,6	150	71,4
Marche R	...N	3	11	5,2	11	5,2	18	110	52,5	108	51,4
	...R	3	22	10,5	16	7,6	11	60	60	154	73,4

Fig. 20: Table summarizes the different phases of the high and medium pressure valve gear

The degree of expansion allowed compels us to recognize the relative smallness of the openings of the ports, so we make the ratios of 11-22:12-22 and 9-11:10-11 as great as possible.

The different positions of point 23 corresponding to the travels of the slide-valve giving the anticipated degrees of admission and of exhaust, we plot the arcs in making the appropriate radiuses so that they intersect at a point located on the vertical axis of the curve described by point 11.

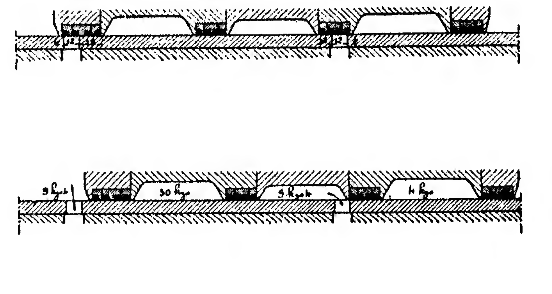
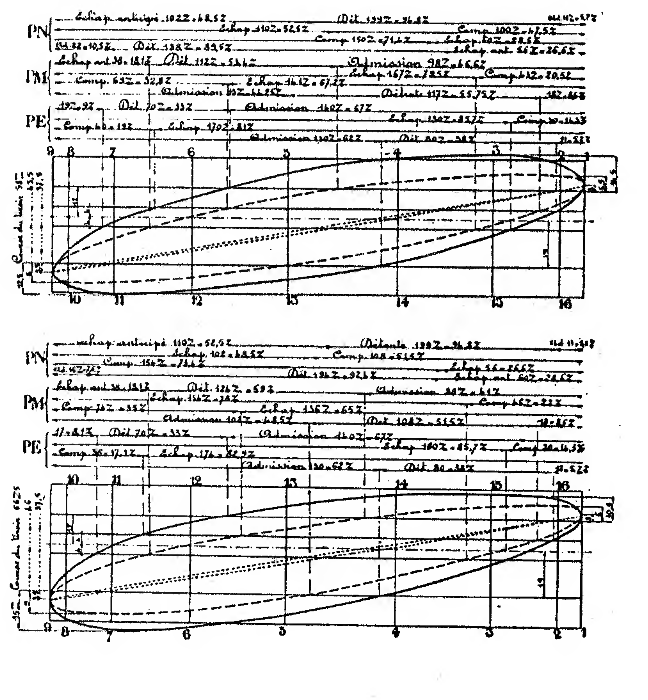


Fig. 22 (above): Position of the slide valve showing lap.
Fig. 23 (below): Postition of the slide valve corresponding to the point 14 and at admission



Curves representing the motion of the high pressure and medium pressure slide valves. Scale 1/3
Fig. 24 (above): Normal operation (N).
Fig 25 (below): Reverse operation (R).

This point where these two arcs intersect constitutes the center of the curves described by the point 22 in the two directions of operation A V and A R.

At the points corresponding in the directions of operation A V and A R to the admissions *a*, *b* exhaust, *c* compression, anticipated for the imposed admission, we place a strip of paper representing the rod 11-22-12 of which the point 22 must be present on the arcs representative of the exhaust and of the admission A V and A R. We proceed to slide this strip of paper maintaining the point 11 on the curve that it describes in its corresponding movement with the rotation of the engine crank; and the point 22 as was said is on the curves A V and A R, which gives us the points 12*a*, 12*b* and 12*c* representing the admission, the exhaust and the compression respectively, relative to the imposed admission.

By a series of experiments we strive to make the axis of sector slide-shaft 13-14 of the reversing gear pass through the points 12*a*, 12*b*, 12*c*. In this way we obtain an average admission of 62% in the high pressure cylinder, 67% in the medium pressure cylinder, and 52.5% in the low pressure cylinder. We have additionally guided our experiments so as to achieve perceptibly smooth operation.

Study of the phases of the valve gear.

In estimating our volumes of displacements, we assume as average pressure in the reheaters 9 kg/cm^2 between the first and the second expansion, and 4 kg/cm^2 between the second and the third expansion.

From the plot of the graphs (Fig. 33) for running as an engine (extreme position) we have for the clearance spaces the approximate volumes of 0.25 liters for high pressure, 0.35 liters for medium pressure and 0.6 liters for low pressure.

Volume of each one of the reheaters, about 42 liters.

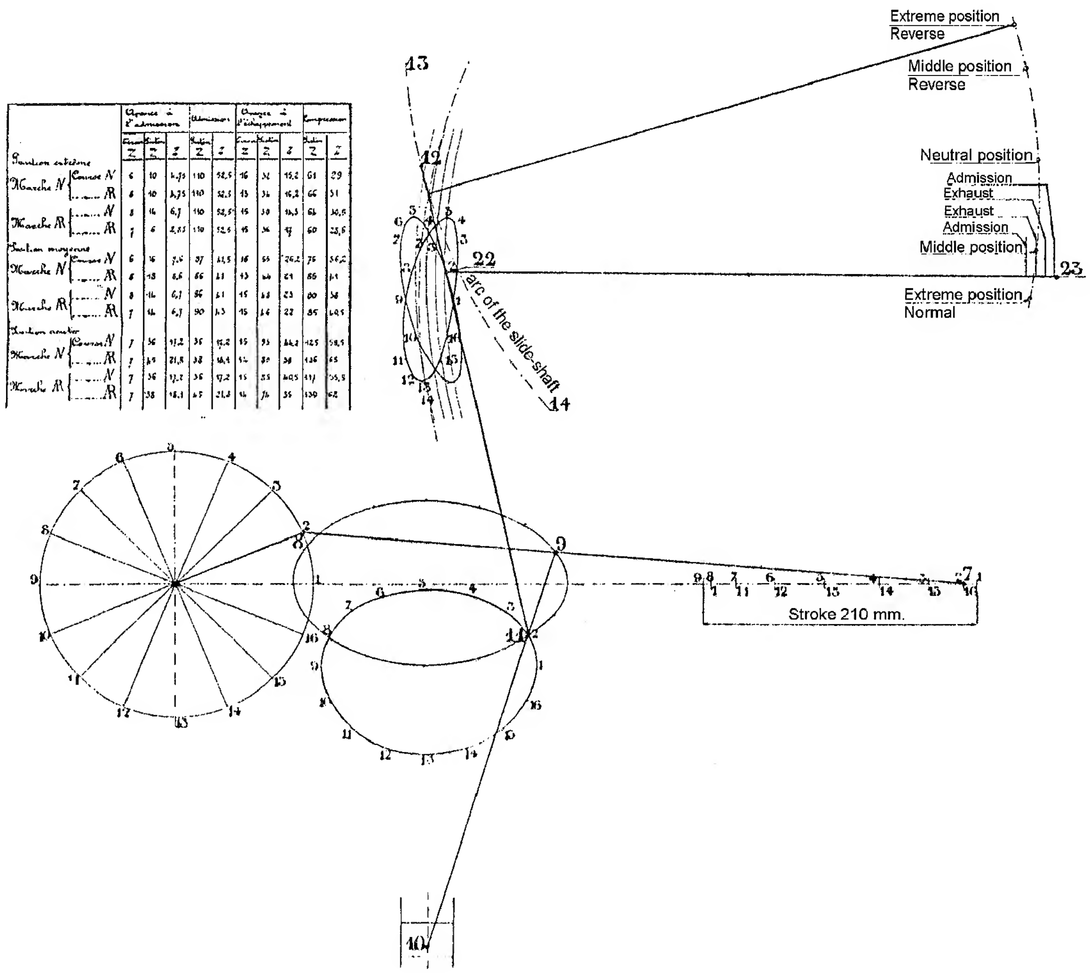


Fig. 21: Table summarizes the different phases of the low pressure valve gear

Volume of one displacement, low pressure: $\dfrac{3.1416 \times 2.42^2}{4} \times 2.1 = 9.5$ liters

Since one displacement of medium pressure must provide the necessary air for two cylinderfuls low pressure, a volume of 9.5 liters × 2 = 19 liters is represented on our graphs (Fig. 33 and 34) by:

$$\frac{210\text{ mm}}{19} = 11.05\text{ mm / litre}$$

Volume of one displacement, medium pressure: $\dfrac{3.1416 \times 1.95^2}{4} \times 2.1 = 6.27$ liters

Represented on the graphs by: 6.27 × 11.05 = 69 mm.

Volume of one displacement, high pressure:

$$\frac{3.1416 \times 1.95^2}{4} - \frac{3.1416 \times 1.6^2}{4} \times 2.1 = 2.05\text{ liters}$$

Represented on the graphs by:

$$11.05 \times 2.05 = 22.5 \text{ mm}$$

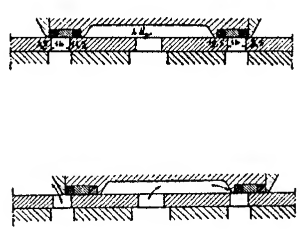
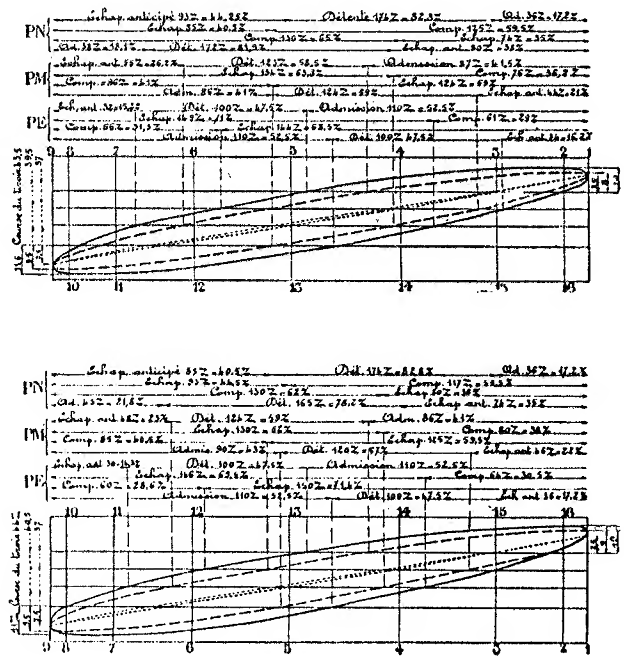


Fig. 26 (above): Position of the slide valve showing lap. Fig. 27: (below): Position of the slide valve corresponding to point 2 and at exhaust R



Curves representing the motion of the low pressure slide valve.

Fig. 28 (above): Running *N* (as engine)
Fig.29 (below): Running *R* (as compressor)

With an admission of 62% to the high pressure cylinder, there would be an introduction of 130 mm (Fig 33), the admitted volume will be $0.976 \times 1.3 = 1.27$ liters.

Adding to it the volume of the clearance space gives us:

$$1.27 \text{ liters} + 0.25 \text{ liters} = 1.52 \text{ liters}$$

By taking into account some throttling and possible resistances we have an admission pressure of 28.5 kg instead of the 30 kg pressure at the working tank.

The volume contained in the cylinder just at the moment of the opening of the exhaust will be:

$$0.976 \times 1.99 + 0.25 \text{ liters} = 2.192 \text{ liters}$$

The pressure will be:

$$28.5 \text{ kg} : \frac{2{,}192^{1.3}}{1{,}520} = 17.8 \text{ kg}$$

In this equation 1.3 represents the exponent corresponding to the polytropic expansion that we have assumed (see Fig 37).

Volume at the beginning of the high pressure compression.

$$0.976 \times 0.36 + 0.25 = 0.6 \text{ liters}$$

Volume at the initial pressure of 30 kg/cm^2.

$$0.6 \text{ liters} : \frac{30}{9.4} \times \frac{1}{1.3} = 0.246 \text{ liters}$$

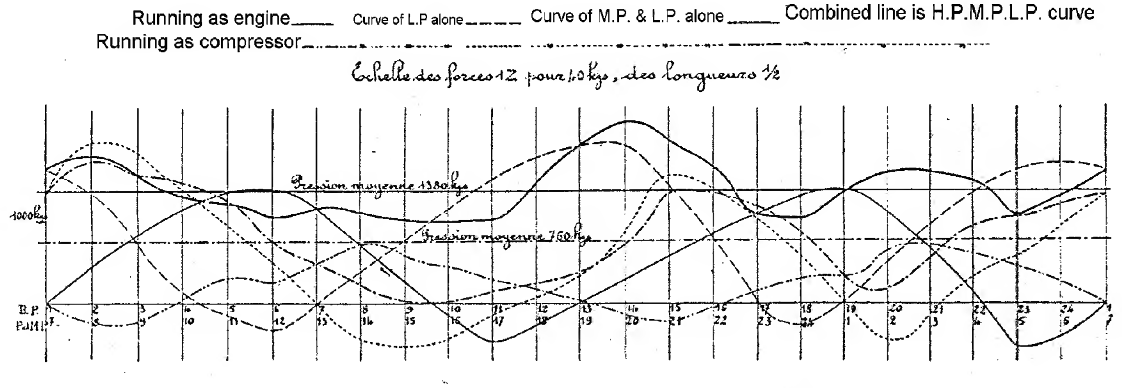


Fig. 30: Curves of tangential effort, admission 62%

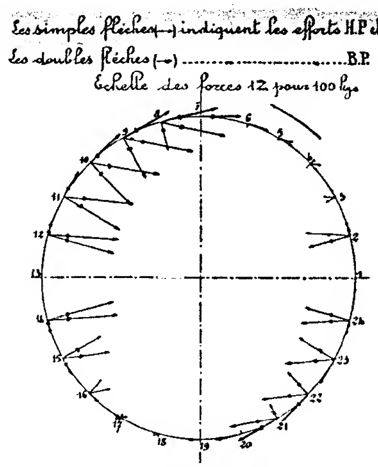


Fig. 31: Analysis of engine effort.

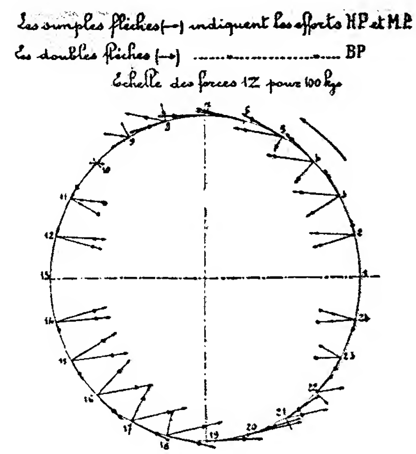


Fig. 32: Analysis of braking effort

According to the examination of the graphs and that which precedes, we see that the volume of air at the initial pressure of 30 kg/cm^2 supplied by the compression phase is hardly sufficient to fill the clearance space.

Volume of the expanded air delivered to the reheater located between the first and the second expansions for the medium pressure, per turn of the crank:

$$\frac{28.5\text{ kg}}{9\text{ kg}} \times \frac{1}{1.3} \times 1.27 = 3.06 \text{ liters at } 9\text{ kg}/\text{cm}^2$$

We assume an average ambient temperature of 15 centigrade degrees or:

$$15° + 275° = 288 \text{ degrees absolute}$$

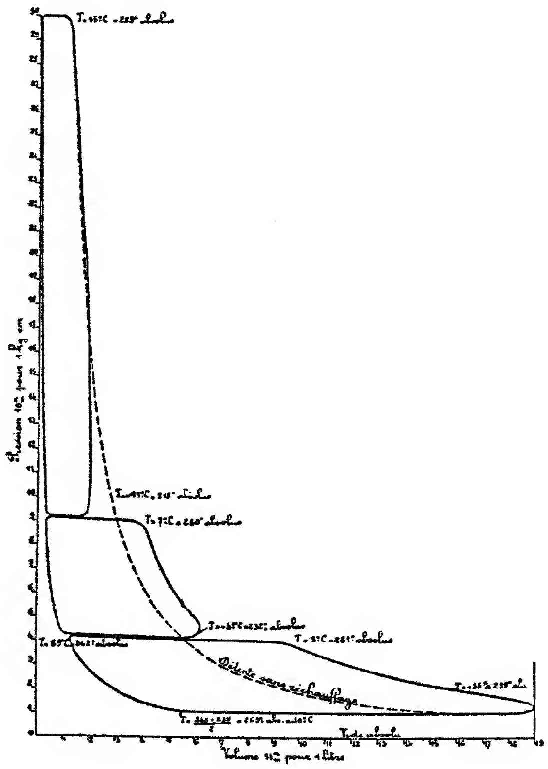
The temperature of the air at the entry of the medium pressure reheater will be:

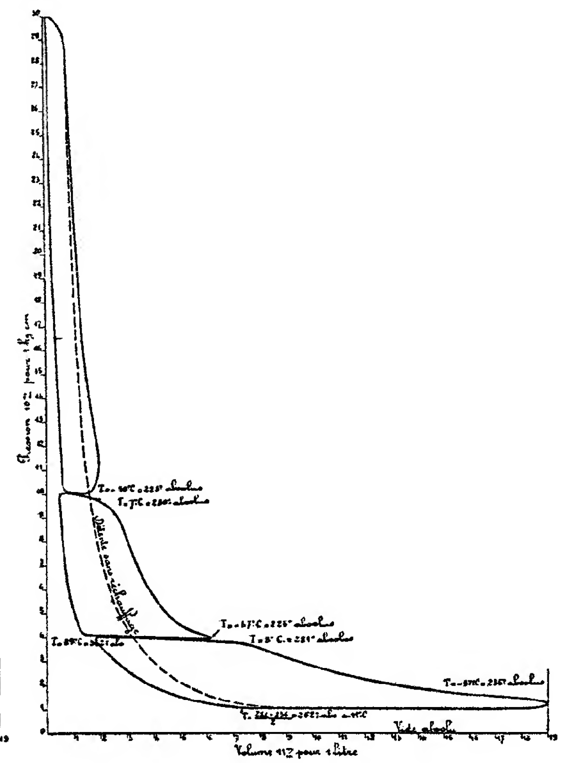
$$288° : \frac{30\text{ kg}}{9\text{ kg}} \times \frac{1.3-1}{1.3} = 218 \text{ degrees absolute}$$

Or 55 degrees centigrade.

Volume of air introduced into the medium pressure reheater per hour, at the speed of 15 kilometers per hour.

$$3.06 \text{ liters} \times 160 \text{ t. m.} \times 60 = 29{,}376 \text{ liters.}$$





Engine diagrams, high pressure

Fig. 33: 62% admission **Fig. 34: 44% admission**

Time taken for one displacement (cylinder charge) to circulate in the medium pressure reheater:

$$1 : \frac{29{,}376}{42} = 0.00143 \text{ k.}$$

Number of calories transmitted by the shell-and-tube reheater (according to the formula book):

$$Q = 1 \times \pi \times Z \times \frac{t1 - t2}{\dfrac{1}{\alpha \times \mathrm{di}} + \dfrac{1}{\alpha \times \mathrm{da}} + \dfrac{1}{2\lambda} \log \dfrac{\mathrm{di}}{\mathrm{da}}}$$

Within which formula:

1 = useful length of the tubes of the shell-and-tube reheater.

t1= temperature of the ambient air.

t2= temperature of the air inside the reheater.

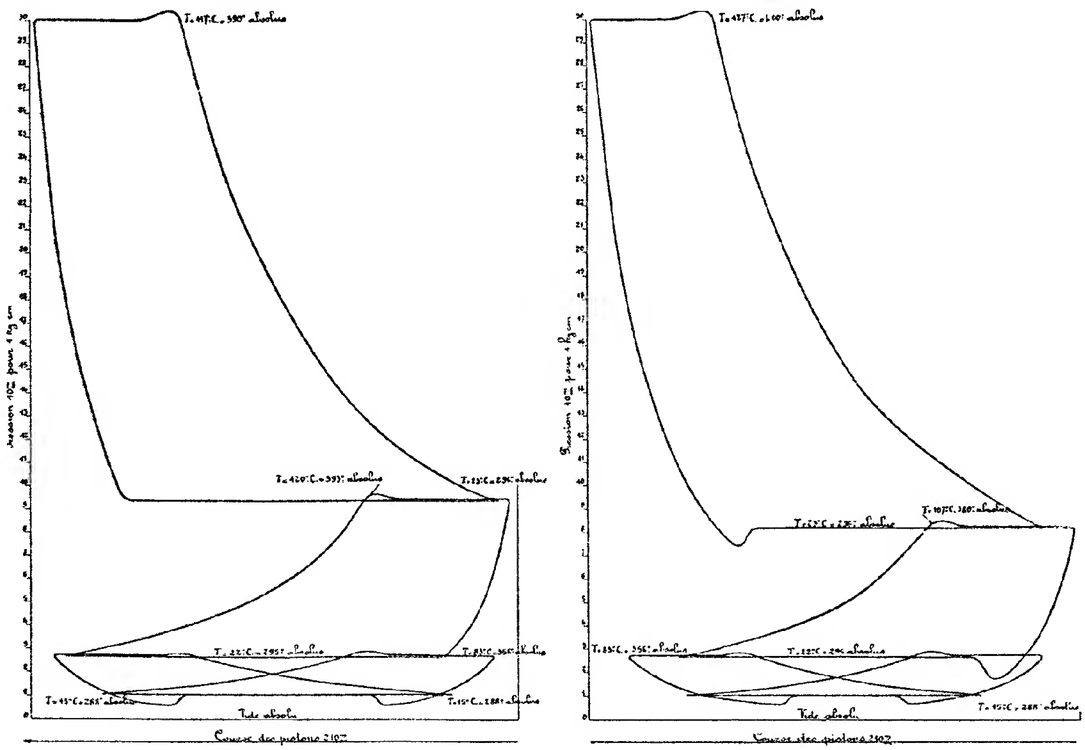
α = transmission coefficient of heat in the air; equal to 5, according to the formula book.

di = inside diameter of the tubes, 20 mm.

da = outside diameter of the tubes, 23 mm.

λ = coefficient of conductibility of the walls, 35 to 45 for soft steel and 55 to 110 for brass; will use 40 and 55.

n = number of tubes, in our case 37.



Braking Diagrams

Fig. 35: 62% notch **Fig. 36: 44% notch**

From there replacing the letters with their values, we obtain:

$$Q = 2 \times 3.1416 \times 0.00143 \frac{288 - 218}{\frac{1}{5 \times 0.02} + \frac{1}{5 \times 0.023} + \frac{1}{2 \times 55} \log \frac{0.023}{0.02}} 37 = 1.25$$

For the tube forming the outer shell of the reheater, we will have:

$$Q = 2 \times 3.1416 \times 0.00143 \frac{288 - 218}{\frac{1}{5 \times 0.212} + \frac{1}{5 \times 0.22} + \frac{1}{2 \times 40} \log \frac{0.22}{0.212}} = 0.34$$

Or a total of 1.25 + 0.34 = 1.59.

We have also $Q = kSz(t1 - t2)$.

Within which formula:

z = the time in hours.

k= coefficient varying with the speed, which we have equal to 2.8 according to the formula book.

S = surface of reheater in contact with the ambient air, in our case equal to 6.23 m^2.

We extract:

$$t1 = \frac{Q}{kzS} + t2.$$

By replacing the letters with their value, we have:

$$t1 = \frac{1.59}{2.8 \times 6.23 \times 0.00143} + 218 = 280°.$$

According to that which precedes we saw that the temperature of the ambient air being 15°, corresponding to 288 absolute degrees, and that the temperature of the air at the exit of the medium pressure reheater is 280°, there is a difference of 8° between it and the temperature of the air at the pressure of initial admission, 30 kg/cm^2.

Upon obtaining the volume of the air the motor admitted to the medium pressure cylinder we admit that this air is expanding according to this difference of temperature of 8°.

According to the formula book we have:

$$\frac{P1^{\frac{n-1}{n}}}{P2} = \frac{t1}{t2}$$

Within which formula:

P1 = the pressure of admission to the cylinder, *ch*.

P2 = the pressure of admission to the medium pressure cylinder.

t1 = the temperature of the air admitted the high pressure cylinder.

t2= the temperature of the air admitted the medium pressure cylinder.

n= exponent for polytropic expansion.

From this formula we extract:

$$\log \frac{P1^{\frac{n-1}{n}}}{P2} = \log \frac{t}{t2} \text{ and } \frac{n-1}{n} = \log \frac{t1}{t2} : \log \frac{P1}{P2}$$

By replacing the letters with their values one obtains:

$$\frac{n-1}{n} = \log \frac{288}{280} : \log \frac{30}{9} \quad \frac{0.013}{0.532} = 0.025$$

And one extracts:

$$N = 1.0255$$

We are going to determine the volume of air in kg/cm^2 available per turn of crank for the medium pressure cylinder; we have:

$$1{,}210 \frac{30^{1.0255} \text{ kg}}{9\text{kg}} = 3.9 \text{ liters}$$

In order to take into account some possible losses, we will have 3.85 liters.

At the beginning of the compression phase the volume will be:

$$\frac{2.98}{\frac{1}{1.3}} \times 0.3 + 0.35 = 1.245 \text{ litres}$$

Volume at the pressure of 9 kg/cm^2.

$$1.245 : \frac{9}{4} \times \frac{1}{1.3} = 0.67 \text{ liters}$$

The volume of admission to the medium pressure cylinder will be, according to that which precedes:

$$3.85 \text{ liters} + 0.67 - 0.35 \text{ liters} = 4.17 \text{ liters}$$

Representing a portion of the stroke equal to:

$$\frac{4.17 \text{ liters}}{2.98} = 140 \text{ mm}$$

The volume contained within the medium pressure cylinder at the moment of the exhaust will be:

$$2.98 \text{ liters} \times 1.91 + 0.35 = 6.05 \text{ liters}$$

With an exhaust pressure of:

$$9 \text{ kg } \frac{6.05}{4.17 + 0.35} \text{ } 1.3 = 6 \text{ kg / cm}^2$$

The volume of the expanded air that will escape into the reheater located between the second and the third expansion or low pressure will be:

$$\frac{9}{4} \times \frac{1}{1.3} \times 3.85 \text{ liters} = 7.15 \text{ liters at } 4 \text{ kg / cm}^2$$

The temperature of the air at the entrance of the low pressure reheater will be:

$$280 : \frac{9}{4} \times \frac{1.3 - 1}{4} = 232° \text{ absolute, or } 41° \text{ C.}$$

The hourly volume of air that enters the low pressure reheater, the locomotive working at the speed of 15 kmh, will be:

$$7.15 \text{ liters} \times 160 \text{ t. m.} \times 60 = 68{,}800 \text{ liters.}$$

Time that it takes for one displacement to traverse the shell-and-tube of the low pressure reheater:

$$1 : \frac{68{,}800}{42} = 0.00061 \text{ hr}$$

Number of calories transmitted to the air by the shell-and-tube of the low pressure reheater:

$$2 \times 3.1416 \times 0.0061 \text{ hr } \frac{288 - 232}{\frac{1}{5 \times 0.02} + \frac{1}{5 \times 0.023} + \frac{1}{2 \times 55} \log \frac{0.023}{0.02}} \times 37 = 0.422 \text{ calories}$$

For the outer tube forming the shell of the low pressure reheater, we have:

$$2 \times 3.1416 \times 0.00061 \text{ hr } \frac{288 - 232}{\frac{1}{5 \times 0.212} + \frac{1}{5 \times 0.22} + \frac{1}{2 \times 40} \log \frac{0.22}{0.212}} = 0.115 \text{ calories}$$

Or a total of 0.422 + 0.155 = 0.537 calories.
From which we get:

$$t1 = \frac{0.537}{2.8 \times 6.23 \times 0.00061} + 232 = 281^\circ \text{ abs.}$$

Volume of air at 4 kg/cm^2 available to the low pressure cylinder per turn of the crank:

$$3.85 \text{ liters} \times 9/3.9 \times 1.03 = 8.65 \text{ liters.}$$

By taking into account the possible losses we will have 8.6 liters per turn of the crank.

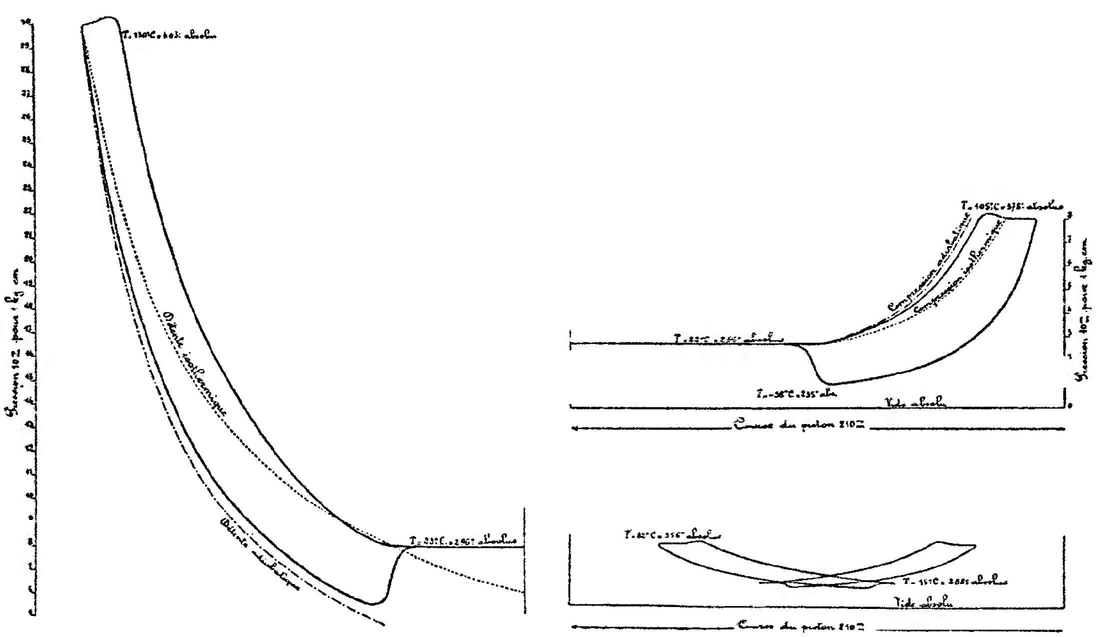


Fig. 37 (above): High pressure diagram, neutral position
Fig. 38 (above right): Medium pressure diagram, neutral position
Fig 39 (bottom right): Low pressure diagram, neutral position

Volume in the low pressure cylinder at the start of the compression phase:

$$4.52 \times 0.63 + 0.6 = 3.45 \text{ liters}$$

Volume at the pressure of 4 kg/cm^2,

$$3.45 \text{ liters} : \frac{4}{1.1} = 1.28 \text{ liters}$$

The volume of admission at each intake per stroke of low pressure piston will be:

$$\frac{8.6 \text{ liters}}{2} \times 1.28 \times 0.6 = 4.98 \text{ liters}$$

Corresponding to one stroke of the piston:

$$4.98 \text{ liters} / 4.52 = 110 \text{ mm}$$

Volume contained in the low pressure cylinder at the moment of the opening of the exhaust:

$$4.52 \times 1.77 + 0.6 = 8.6 \text{ liters}$$

At a pressure of:

$$3.9 : \frac{8.6^{1.3}}{4.98 \times 0.6} = 2.23 \text{ kg} / \text{cm}^2$$

At a temperature of:

$$281 : \frac{3.9^{\frac{1-3-1}{1.3}}}{2.23} = 239° \text{ abs.}$$

In operating as previously for the other degrees of admission and working as a compressor, we have obtained the necessary data to enable us to do the plotting (Fig 34, 35, 36, 37, 38 and 39) of the different graphs.

In order to draw the curves of the tangent efforts we divided the circumference described by the crank into 24 equal parts and determined the corresponding efforts at every corresponding point (Fig. 31, 32, 38 and 39), with the stroke of the piston divided also into 24 parts; we have analyzed tangent efforts and efforts by the engine shaft.

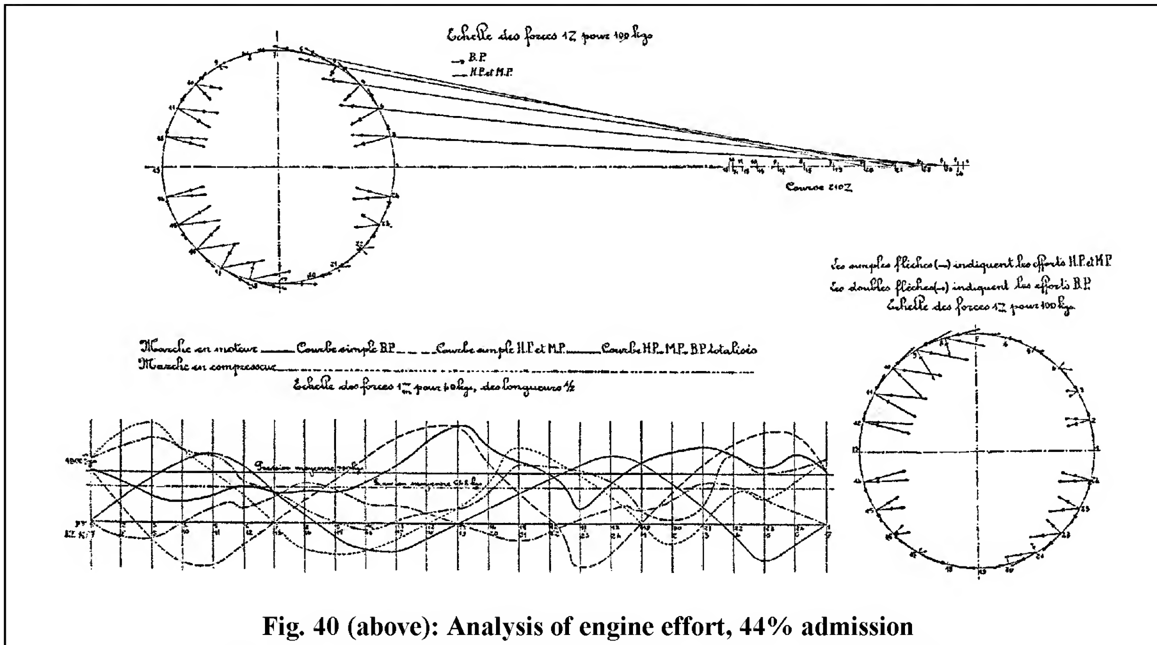


Fig. 40 (above): Analysis of engine effort, 44% admission
Fig. 42 (bottom left): Curves of tangential effort, 44% admission
Fig. 44 (bottom right): Analysis of braking effort

On a horizontal of a length representing the evolution of the circumference described by the engine crank (Fig 30 and 40), we mark the previous divisions and at the different points obtained on the perpendiculars that are there elevated, at a suitable scale the different efforts that enable us to draw the representative curves of the efforts of the high pressure, medium pressure and low pressure pistons.

We obtain in this way an average effort of 1,380 kg for the running of the engine with an admission of 62% at the high pressure cylinder.

710 kg for running as a compressor with the reversing gear lever at the 62% admission notch.

900 kg for running as an engine with an admission of 44% to the high pressure cylinder.

648 kg for running as a compressor, the reversing gear lever at the 44% notch of admission.

Determination of the power and consumption with 62% admission to the high pressure cylinder.

We saw previously that the number of liters of compressed air at the initial pressure of 30 kg/cm^2 admitted to the high pressure cylinder according to the graph is 1.21 liters.

The number of kilogram-meters developed per turn of crank is:

$$1{,}380 \text{ kgm } 3.1416 \times 210 \text{ mm} = 910 \text{ kgm.}$$

By taking into account a minimum total efficiency of 75% for the whole of the machine, at the speed of 12 kmh the developed power will be:

$$\frac{910 \text{ kgm} \times 2.1 \text{ t} \times 0.75}{75} = 19.11 \text{ cv}$$

The traction effort will be, with wheels of 0.5 m diameter:

$$\frac{910 \text{ kgm} \times 0.75}{1.56 \text{ m}} = 437 \text{ kgm}$$

By taking into account a rolling resistance of 13 kg per gross pulled ton and a weight of 6,500 kg for the locomotive in working order, we will pull on a level:

$$\frac{437 \text{ kg} - (6.5 \text{ t} \times 13 \text{ kg})}{13 \text{ kg}} = 27 \text{ tonnes}$$

Let us assume the empty truck weighs 300 kg and that the typical load of coal is 600 kg, which is 900 kg per full truck.

With an admission of 62% to cylinder P, on a level and at the speed of 12 kmh we will pull:

$$27{,}000 \text{ kg} / 900 \text{ kg} = 30 \text{ trucks.}$$

Against a slope equal to a resistance of 5.5 millimeters per meter in favor of the load, the number of pulled trucks will be:

$$\frac{437}{13 - 5.5} = 6.5 \text{ t} : 0.9 \text{ t} = 56 \text{ full trucks.}$$

Upon this slope of 5.5 millimeter, at the speed of 12 kmh, we can pull a number of empty trucks equal to:

$$\frac{437}{13\text{ kg} + 5.5} = 6.5\text{ t} : 0.3\text{ t} = 56\text{ empty trucks.}$$

The theoretical consumption per kilometer, without taking into account the regenerative braking or the heat developed by running as a compressor will be:

$$\frac{1 : 210 \times 1000}{3.1416 \times 0.5} = 775\text{ litres of air at 30 kg / cm}^2$$

Or:

$$775\text{ liters} \times 30\text{ kg} = 23{,}200\text{ liters of air at atmospheric pressure.}$$

The consumption per useful pulled ton will be:

$$\frac{23{,}200\text{ liters} \times 2}{0.6\text{ t} \times 56\text{ b}} = 1{,}385\text{ liters at 1 kg / cm}^2.$$

The useful capacity of the tanks of the locomotive being 1,212 liters, and by taking into account a fall of pressure of 2 kg at the maximum in order to account for the losses of a one one-way trip and return, the charging being to the pressure of 150 kg/cm^2, the volume of available air at the pressure of 1 kg/cm^2 assuming a residual pressure of 28 kg/cm^2 in the tanks of the locomotive after a one-way journey and return, will be:

$$(1{,}212\text{ l.} \times (150\text{ kg} - 2\text{kg}) - (1{,}212\text{ liters} \times 28\text{ kg}) = 146{,}000\text{ liters.}$$

Useful travel of the locomotive, in meters, will be:

$$\frac{146{,}000\text{ litres}}{23{,}200} = 6{,}300\text{ meters.}$$

We will determine to adhere to the stopping of a train of 56 trucks with braking done by running the unit as a compressor, by putting the lever of the reversing gear at the 62% admission notch, and without making use of the bypass starter, the lever of the reversing gear enabling the immediate stopping of the machine.

We suppose that the stop must be produced when the train of trucks runs at the speed of 12 kmh or 3.33 m to the second.

Weight of the train with 56 full trucks of coal:

$$(900\text{ kg} \times 56) + 6{,}500\text{ kg} = 57{,}500\text{ kg.}$$

Kinetic energy of this train at 3.33 m per second:

$$\frac{57{,}500\text{ kg} \times 3.33^2}{2 \times 9.81} = 32{,}500\text{ kgm.}$$

Against the steady slope of 5.5 mm per meter resistance, the power absorbed by the rolling resistance will be: 57,500 kg $\times$ (13 kg + 5.5 kg) $\times$ 3.1416 $\times$ 0.5 m = 672 kgm.

Power from braking per turn of wheel, by taking into account that in the course of running as a compressor the lever of the reversing gear is at the 62% admission notch, yields an effort of 760 kg as we saw previously:

$$\frac{760 \times 0.66}{0.75} = 670 \text{ kgm.}$$

Number of wheel turns necessary in order to obtain the stopping of the train:

$$\frac{32{,}500}{672 \times 670} = 24.2 \text{ revolutions}$$

Corresponding to a distance traversed:

$$3.1416 \times 0.5 \text{ m} \times 24.2 \text{ t} = 37.8 \text{ m.}$$

Weight of a train of empty trucks:

$$(300 \text{ k} \times 56) + 6{,}500 = 23{,}200 \text{ kg.}$$

Kinetic energy of this train at 3.33 m per second:

$$\frac{23{,}200 \text{ kg} \times 3.33}{2 \times 9.81} = 13{,}150 \text{ kg.}$$

Power absorbed by the resistance to the rolling of this train against the slope of steady resistance of 5.5 millimeter per meter:

$$23{,}200 \times (13 + 5.5) \times 3.1416 \times 0.5 = 670 \text{ kg.}$$

Number of wheel turns necessary to stop this train:

$$\frac{13{,}150}{670 \times 670} = 9.8 \text{ t}$$

Or a trip of:

$$3.1416 \times 0.5 \text{ m} \times 9.8 \text{ t} = 15.3 \text{ m.}$$

Determination of the regenerative braking

The number of liters of compressed air at 30 kg/cm^2, recovered per turn of the wheel, the lever of reversing gear being at the 62% admission notch at the high pressure cylinder, is 0.557 liters, according to the diagrams.

The number of liters of air at the pressure of 1 kg recovered by braking for one one-way trip with a train of empty trucks is:

$$0.557 \text{ liters} \times 9.8 \text{ t} \times 30 \text{ kg} = 164 \text{ liters.}$$

The number of liters of air at the pressure of 1 kg recovered by the brake for one return trip with a train of full trucks is:

$$0.557 \text{ liters} \times 24.2 \text{ t} \times 30 \text{ kg} = 403 \text{ liters.}$$

We allowed the minimum of braking, that is to say one braking at each end of the trip (in practice there could be more than two operations of the brake); in that event total recovery will be:

403 liters + 164 liters = 569 liters.

These 569 liters of air at 1 kg/cm^2 recovered on a trip of 6,300 meters, would be:

569/6.3 = 90 liters per kilometer.

The consumption per gross kilometric ton pulled with recovery will be:

$$\frac{(2.32 \text{ liters} - 90 \text{ litres})\ 2}{(0.9\ t \times 56) + (0.3\ t \times 56)} = 660 \text{ litres of air at } 1\ kg / cm^2.$$

The consumption per useful kilometric ton pulled with recovery will be:

$$\frac{(2.32 \text{ liters} - 90.2 \text{ liters})}{0.5\ t \times 56} = 1{,}330 \text{ litres of air at } 1\ kg / cm^2.$$

In our study, given the great difficulties of estimating the real temperatures that would be obtained, we didn't attempt to take into account the heat recovered at the end and in the course of each trip during the periods of braking; this is a factor that will certainly be shown to decrease the consumption even more.

CONCLUSION

With this exposition, we have again brought out the advantages resulting from the arrangements that we have adopted from the point of view of consumption, which is of a large importance not only because one realizes an economy that lowers the price of returns of the kilometric useful ton, but as well as it enables a radius of larger action to the machine, and also increases available workspace, therefore one has double interest in having a locomotive as economical as possible.

Some builders adopted, and ourselves in the beginning, some apparatuses as costly as complicated for reheating with superheated water, till coming eventually to the use of the heat of the ambient air, by which the relatively low efficiency was far from being comparable to our apparatus of reheating with the heat recovered by running as a compressor for the stop at each end of the trip in one direction or the other.

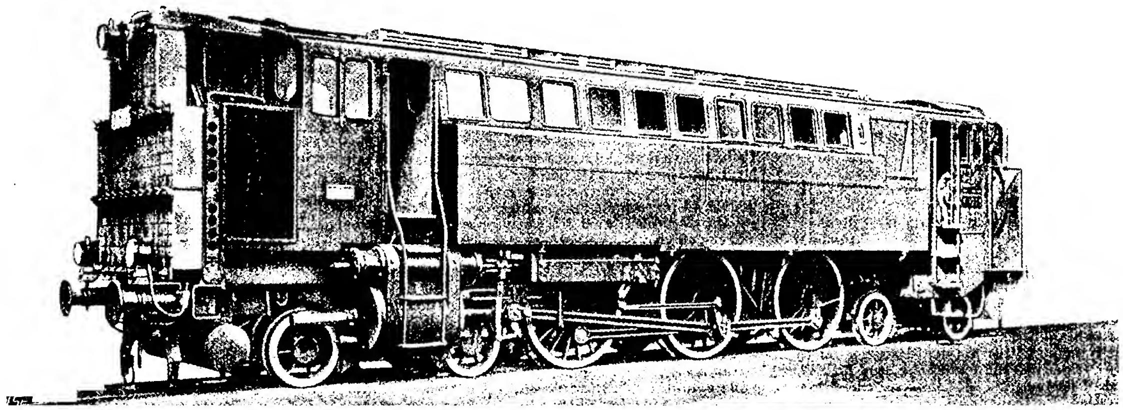
The safety is absolute with the use of our bypass starter for the starting and the instantaneous stopping of the convoys, and which enables the mechanic to be absolutely sure of his machine, of adopting an average speed of fifteen kilometers per the hour and of increasing the useful output substantially per period of working.

By the disposition of a winch in the front of the machine, we will take the trucks into the lateral galleries of demolition of which the small section doesn't permit access to the locomotives, we think it could be possible in this way to remove the horses from under ground completely.

We endeavored, on behalf of our new locomotive, in drawing inspiration from the current needs of the mining industry, to gather all the known perfections until this day. And, while being of a simplest construction, of an absolute security, of using the compressed air in a rational way under a great reduction of congestion in the workplace.

Author's Note: Similar machines are in the process of implementation at the shops of the Compagnie de Fives-Lille for the salt mine and the Reichsland potash, at Wittenheim (Haut Rhine).

The 1200 Horsepower Diesel-Pneumatic Hybrid Locomotive, 1930

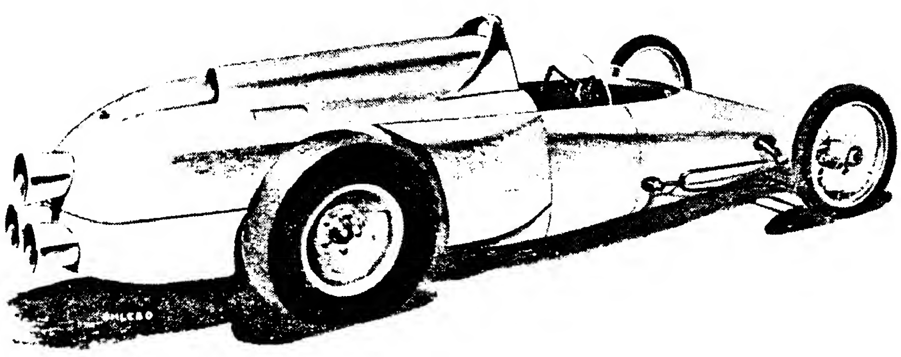


"1200 B.H.P. Diesel-Compressed Air Locomotive for the German State Railways," ***The Engineer*****, May 2, 1930,**

One of the overlooked casualties of World War II is the destruction of the thriving European market for compressed air locomotives, including hundreds if not thousands of triple expansion straight pneumatic locomotives used in coal mines all over Europe, until something about the war made all this stuff mysteriously disappear. For more information on hybrid pneumatic vehicles, see Chapter 6. This one used 26% less diesel fuel than a straight diesel locomotive, because the compressed air was used as a heat sponge to cool the diesel engine; the absorbed heat is straight air car fuel. Was the destruction of the European compressed air locomotive a purposeful "black operation" of WWII, or is it just a coincidence that the air engine became unmentionable in the textbook environment sometime after 1931?--Editor

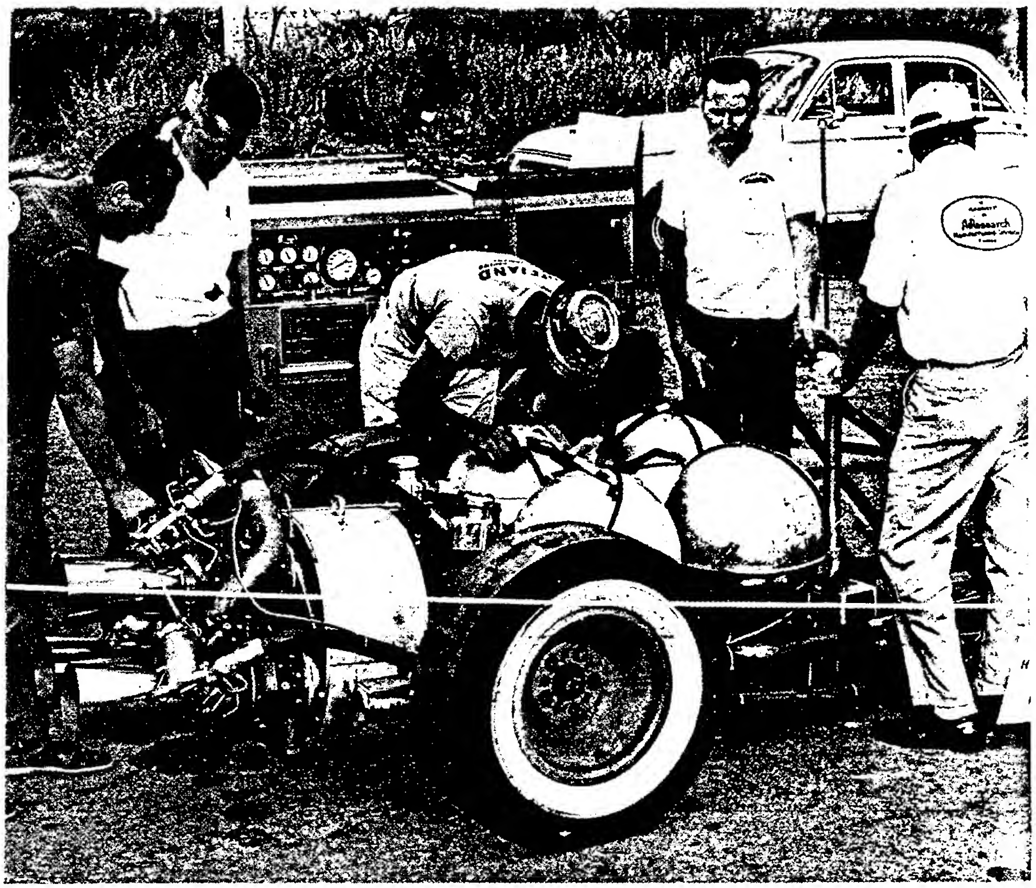
Air Powered Race Car, 1962

"Dragging on Air!," Motor Trend, September 1962



Jet aircraft starter motors using compressed air as fuel provide the unique power for this experimental dragster that has covered the quarter-mile in the nine-second range

Drag fans around the country will soon be treated to something different in dragsters when the Speed-Sport Shop Special fires (?) up for a nationwide tour. Long famous for their 170-plus-mph modified roadster, the Tucson, Arizona speed merchants



The air dragster's crew checks out the compressed air tanks before one of the trial runs held recently in Phoenix, Ariz.

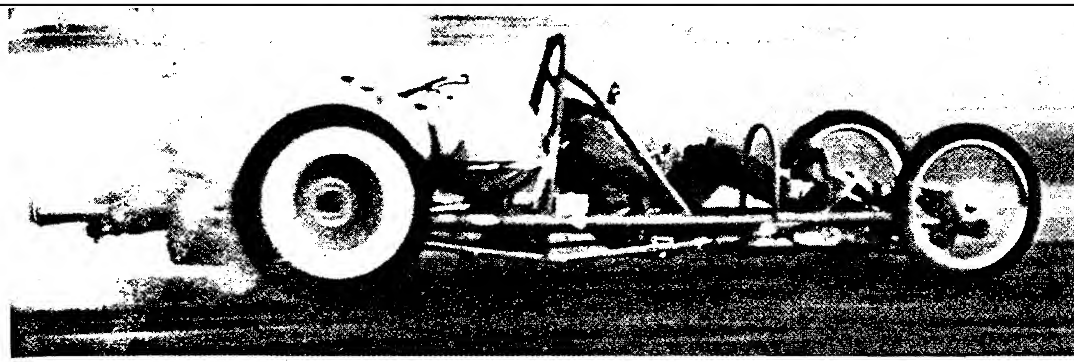
have forsaken their fuel-burning monster to come out with the world's first air turbine-powered car.

Driven by three modified jet aircraft starter motors, manufactured by AIResearch's Phoenix division, the dragster used compressed air as fuel.

The starters were originally designed to boost jet engines, such as those used in the Boeing 707, to starting speed. The compact units each weigh 35 pounds, and in a slightly modified form each puts out 200 air horsepower.

Air for the units is contained in lightweight aircraft air bottles mounted behind the driver. A 15-second supply of air at 3000 pounds per square inch powers the 3/4-ton rail.

This air, heated by combusters, spins the turbine wheels in each of the starters at 70,000 rpm. Reduced through gearing, this reached the differential at 8000 rpm. Early tests have produced speeds in the 160-mph, nine-second e.t. range.



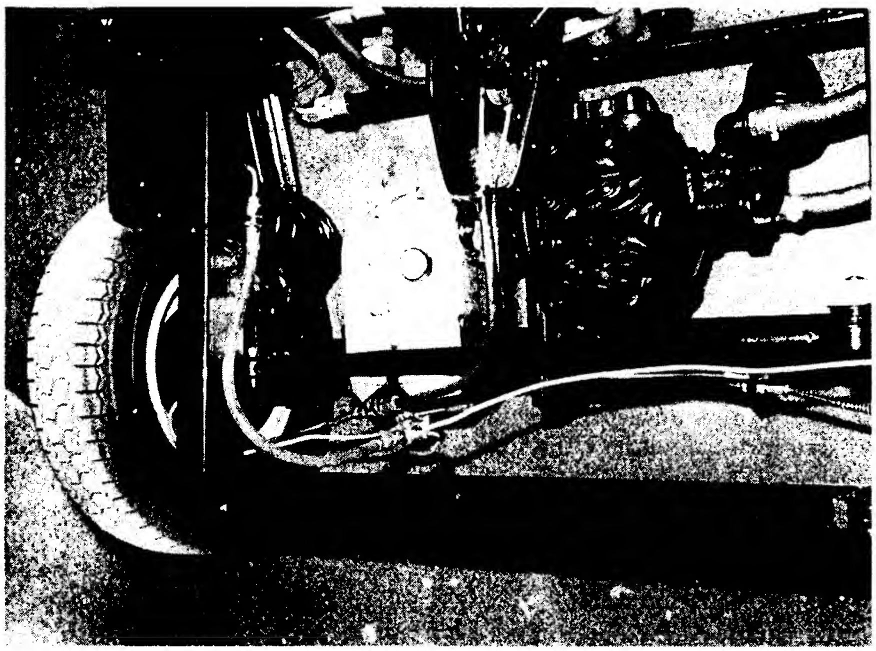
Screaming like a banshee, the revolutionary Speed-Sport car lights up the tires on one of its nine-second quarter-mile test runs.

Sorogato's Air Car, 1975

"Air Car Rivals Electric," Automotive Engineering, vol. 83, January 1975, p. 25.

Compressed air drive is proposed by Sorgato in Italy as a viable fuel-economy alternative to the electric car for industrial and urban use. Originally conceived for operation in hazardous areas such as mines and chemical plants where ignition or other electrical discharges could spark off an explosion, the basic concept consists merely of a bank of storage cylinders feeding an air motor through pressure-reduction and throttle valves.

The first experimental model, built to demonstrate the idea, has nine air bottles charged to 2840 psi by an external compressor. This pressure is reduced to 85 psi for the five-cylinder radial motor, which drives the rear wheels through a simple reduction gearbox with integral differential.



Top speed of this near-silent and non-polluting vehicle is 30 mph, and duration is said to be about two hours. A forward/reverse valve controls direction of travel. The chassis illustrated weighs 770 lb. Advantages claimed for pneumatic drive over conventional storage batteries are rapid recharging (time dependent solely on the supply pressure available), simple speed-regulation, low cost construction and light weight. Further development of the air storage system and motor is underway, and the company plans to market small delivery vans based on a refined version of the present chassis design.

Terry Miller's *Spirit of Joplin,* 1993

"With more than a little enthusiasm (Editor's Page)", by Richard T. Schneider, p. 4, and "Air-powered car rolls through Joplin, Missouri", by Richard T. Schneider, p. 6, Hydraulics and Pneumatics, August 1994

Editor's Page: With more than a little enthusiasm

This magazine traditionally focuses on mobile equipment in the same issue that previews the annual SAE International Off-Highway and Powerplant Congress & Exposition in Milwaukee, the largest industrial show that spotlights components for such equipment. Because mobile equipment is literally married to hydraulics, we seldom can find a pneumatic application to tie into that umbrella topic.That situation seemed to be changing last year when we received a clipping from a Missouri newspaper about an air-powered car. The article was very light on technical details (I drew a mental picture of an on-board engine-driven compressor supplying air motors at the car wheels), so we wrote back to ask for more design information. This request resulted in a phone call from Toby Butterfield, who quickly explained how far off the mark my guess had been.Toby is vice president of the International Pneumatic Urban Commuter Club in Joplin, Mo. He explained that the club's roots go back to 1983, when Terry Miller patented an engine powered by multiple pneumatic cylinders and valves, and using sequential expansion of compressed air. The club was formed to support and promote this new concept for transportation in vehicles similar to conventional motor cars. Members wanted to make Joplin the first center for teaching about and demonstrating the practicality of a new method of commuting. They liked the term environmentally gentle, and augmented it with low cost and zero emission. Their mission expanded into its hardware phase by selling stock in Pneumacom, Inc., a more formal corporate entity. Proceeds from the sale were combined with donations from club members, merchants, boosters, and just plain interested individuals to fund a drivable demonstration model. Components donated by supportive industries helped to make this project a reality. The resultant vehicle is described in our "Ideas & Applications" department, which follows on page 6. The Club believes that they are unique as air-car developers. Mr. Butterfield points out that for well over one hundred years researchers have tried to produce a battery to power electric motor cars. Even with Detroit's Big Three finally giving more than lip service to the quest today, a practical battery continues to elude them. The high-pressure pneumatic battery pack in the air-powered car may be the breakthrough that has escaped them so far. It certainly appears that sometime in the future the American public will be forced to make a change in its driving habits and its attitude toward automobiles--probably making the car less of a cultural icon or personal statement than it is today. What form the car of the future will take is still unclear, but if enthusiasm in 1994 is a factor, the air-powered car will be a contender.

Dick Schneider, Editor

Air-powered car rolls through Joplin, Missouri

By Richard T. Schneider

Air hoses showing in grill area are first external hint that Spirit of Joplin is not a conventional, gasoline engine automobile.

From a distance, The Spirit of Joplin looks like any other 1988 front-wheel-drive Chevrolet Sprint, but under the hood there's a major difference. This demonstration car is powered by compressed air—which, of course, produces no undesirable emissions.

The Spirit of Joplin is the most visible aspect of an ongoing teaching and demonstration project led by Pneumacom, Inc., with the goal of proving the practicality of air power for urban transportation. Its logical basic concept: if you remove the heaviest part of a traditional, gasoline-powered automobile—the engine—what's left will require less power to move.

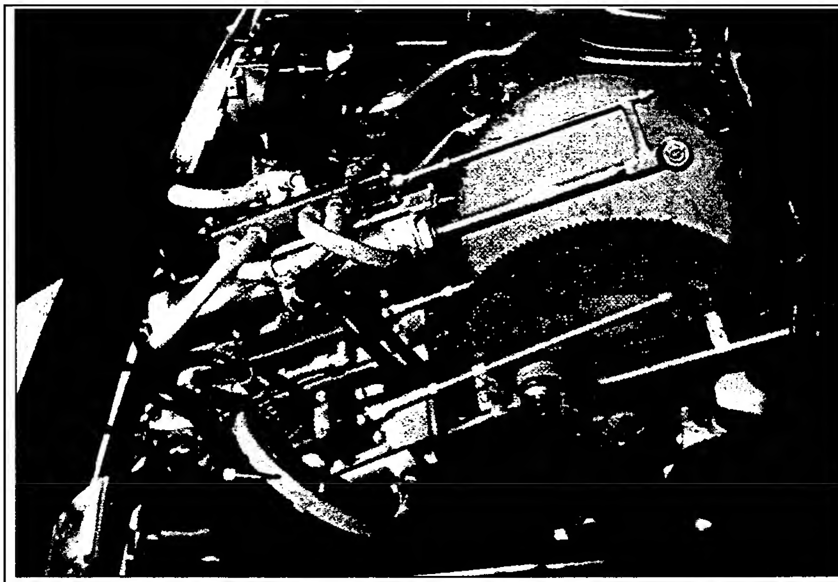
The Sprint's internal combustion engine has been replaced by a patented arrangement of four 10-in.-stroke, double-acting pneumatic cylinders (two for each front wheel) that power the car in a mode similar to a fixed 7:1 gear ratio transmission. This type of acceleration and a top speed of 35 mph are fine for commuting in Joplin traffic. A manifolded 3-pack of cylindrical receivers, reinforced with carbon-fiber wrapping, in the rear of the car holds enough 3000-psi air to provide the 1500-lb Spirit with a 50-mile cruising range.

The cylinder bore diameters are progressively larger—2, 2-1/2, 3, and 4 in. —and they are piped in series fromsmall cylinder exhaust port to next-larger cylinder inlet port. The result: each cylinder delivers about the same force to its crank to drive the Spirit's wheels. To relieve the backpressure that would impede their pistons, the cylinder's piped exhausts vent automatically at mid-stroke. Venting is timed to coincide with each crank's maximum torque position. The cool-running engine (typical maximum speed: 40 rpm) produces little vibration and no heat. It requires no case oil and filter, ignition and carburation systems, or radiator and antifreeze.

Steering has not been changed, and conventional hydraulic brakes stop the car with the original brake pedal. Reversing the cylinder power strokes reverses travel direction. Other driver controls are on/off valves for each receiver, an adjustable pressure regulator (mounted between the two front seats) that limits inlet pressure to 500 psi and also serves as a manual throttle, and a conventional parking brake.

The first of nine planned compressed-air refill stations to be located in Joplin uses an engine-driven compressor. The V-8 engine is carburated to burn natural gas directly from a commercial service meter. Stationary exhaust scrubbers hold engine emissions to a minimum. When the demonstration car pulls in for a refill, a simple pneumatic quick-acting coupling makes the compressor-to-receiver connection.

Earlier this year, The Spirit of Joplin successfully completed a 12-hour endurance test, with time out for refilling and short breaks, at speeds of 30 to 35 mph to add more credence to its practicality. Future plans call for substituting lightweight composite cylinders, adding more receiver volume to increase range, and installing 3- or 4-speed transmissions to improve acceleration and top speed, making driving even more like conventional automobiles. Roof-mounted solar panels could power a radio and other electrical accessories.



Four double-acting pneumatic cylinders drive cranks to power each drive wheel.

Among corporate donor/sponsors who contributed to the air car are: Bimba Mfg. Co., Comdyne 1, Inc., Ingersoll-Rand, Linn Gear Co., Luxfer USA Ltd., Rexroth Worldwide Pneumatics, and Sherwood Div. of Harsco Corp.

"Spirit of Joplin blows into town," Jonathan Beard, New Scientist, August 6, 1994, p. 21

While car makers around the world are struggling to develop exotic batteries and ultra-high-speed flywheels to power the nonpolluting car of the future, a team of researchers in Joplin, Missouri. has been road testing a zero-emission car that runs on compressed air.

"Most of the car is not custom-built, and we had no government funding," says Toby Butterfield, vice-president of Pneumacom, the company that built the car. "We began with a 1988 Chevrolet Sprint, and removed the gas tank, engine and transmission. We replaced the tank with three air cylinders." These are wrapped in fibreglass and carbon-fibre and contain air compressed to 20 megapascals, about 200 times atmospheric pressure.

The compressed air is fed by a hose to two engines, each driving one of the front wheels of the car. The left engine has two double-acting cylinders, one 50 millimetres in diameter with a 254-millimetre stroke, and the other with a 63-millimetre bore. The air enters the first cylinder at 3-5 megapascals, expands to drive the piston, and is then exhausted into a holding chamber, to be fed into the second, larger cylinder.

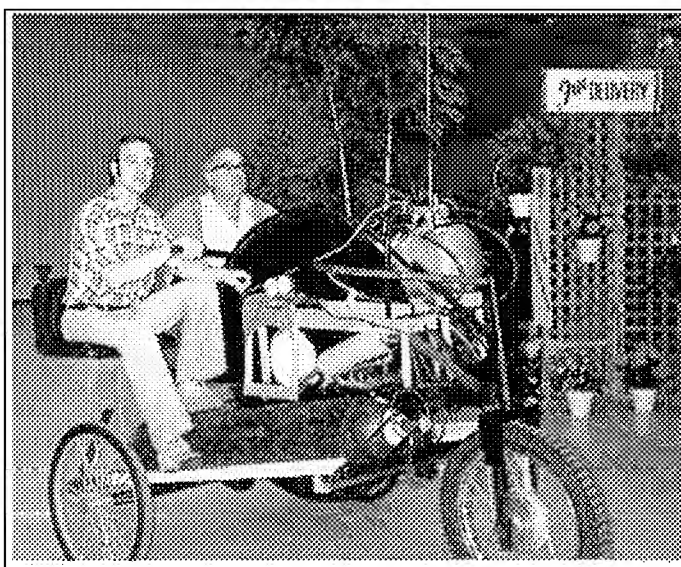
A second hose takes the exhaust from the left engine to the first cylinder of the right engine, which has a 76-millimetre bore. The exhaust from this cylinder drives the fourth cylinder, which has a bore of 105 millimetres. Air leaves this cylinder at only 25 per cent above atmospheric pressure, and is vented.

The piston rods on each engine turn a 140-tooth gear wheel, which in turn drives a 20-tooth gear on each front wheel. “In this prototype, the fixed 7:1 ratio allows the engine to drive the car at a top speed of about 60 kilometres per hour,” Butterfield says.

In March the team tested the car, named Spirit of Joplin, by driving it for 12 hours through the traffic of its home town, stopping only to change drivers and refill the air tanks. A charge lasts two and a half hours, and refilling takes about four minutes.

The compressed air comes from Pneumacom's own “filling station”, a compressor powered by a standard V8 engine, modified to run on natural gas to reduce emissions. “But compressed air at this pressure is not hard to find,” Butterfield points out. “We could stop at any fire station or scuba shop, and use the air they fill breathing tanks with.”

The Pneumacom system was designed by the company's president, Terry Miller, an engineer in Joplin. “Most components were donated, and the labour was volunteered. I estimate that a production vehicle would cost about $10 000,” he says. With funding from government, or the compressed-air or hydraulics industries, he believes that the firm could produce a car with greater range, a more efficient engine and a multispeed transmission, giving it the handling of a petrol-powered car and a top speed of 90 kilometres per hour.



Terry Miller let me drive his air car. The two of us are shown here together. Terry is the greatest air car advocate of the 20th century. Thanks, Terry.